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ON THE ROTATION OF THE EARTH DURING ITS EVOLUTION

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Abstract--Several models are necessary for the study of the rotation of the Earth during its whole evolution. For the fluid state we adopt a zonal rotation with angular velocity increasing from the poles to the equator. After the formation of the Earth's crust the zonal currents in the core seem to have very important influence on the formation of the continents and mountain building. A certain "mean" rotation of the crust about the same axis can be explained by their action. But there are two factors more: the asymmetry of the distribution of masses in the crust and the ceaseless adaptation of the whole Earth to figures of equilibrium corresponding to different positions of the axis of rotation (for this model there are three axes of rotation to be defined). The migration of the poles seems to be explained by a theorem of Milankovitch. The path of the North Pole, for example, since the Silurian may be represented by parts of three paths corresponding: to a single continental block, to an intermediate state, and to the present distribution of continents.

General considerations--The most simple hypothesis on the rotation of the Earth, that the planet rotates like a rigid body, should have been abandoned at the end of the Nineteenth Century. Variations of latitude suggested various solutions of the problem and the purpose of many investigations was to prove such solutions. But the evolution of the Earth is a progressive process and for the geological periods an aperiodical case may be of more importance than any other periodical changes of rotation that occurred in even some thousands of years. DARWIN [1910, p. 10] put forward the idea of the influence of geological changes on the Earth's axis of rotation. He suggests that "if the Earth were a viscous fluid" there is no doubt but that the pole of figure would tend to displace itself toward the instantaneous axis of rotation. On the other hand, if we assume that frictional forces acted in the Earth, there is a limit state to be expected." The following theorem of JOUKOWSKY [1885] deals with this question. "If a rigid body has a cavity filled with a viscous fluid and if this system has an arbitrary distribution of initial velocities, its motion will tend to a final state, by which a principal axis of inertia of the system will have the direction of the initial moment of momentum. The whole system will then rotate about this axis as a rigid body with a constant angular velocity equal to the quotient of the moment of momentum by the moment of inertia about its axis." This conclusion can be also generalised for some other systems [STEKLOFF, 1909; JARDETZKY, 1935]. But if there are some external forces acting on a body, they can hinder the amortizement of the internal movements and change the moment of momentum.

Many different models were proposed for the explanation of the behaviour of the Earth during its evolution, and it is well known that no one is generally adopted. That may be not astonishing since each theory put forward the importance of some new factor. We can distinguish the following groups of factors, about which independent hypotheses can be adopted: (1) the physical state of the Earth involving the internal forces (such as elastic or plastic state of the whole Earth, rigid shell and liquid core) (2) symmetrical or asymmetrical distribution of masses; (3) the existence of external forces.

It is obvious that in general the kind of rotation depends on all these factors, but the difficulty of the problem forces us to make assumptions about the rotation itself independent of other conditions. In many treatments of the problem of the Earth's rotation such an assumption involves a solution, which consequently will hardly correspond to the true motion, as it can be demonstrated by other data. There are assumptions about the kind of rotation, which seem to be less arbitrary for the treatment of the problem; that is, we can consider the initial motion during a short time-interval, and suppose that the components of the angular velocity are of various orders of magnitude. Such a condition can hold in some cases but will be wrong perhaps in some other.

It is easy to see that with a single model we can not explain the rotation of the Earth during its whole evolution. Between the state of quasi-uniform rotation of a liquid mass and the motion of a quasi-rigid body of our days, there were some intermediate states. The representation of these must be chosen in a way which considers all the data of the evolution of the Earth. In particular, it is not permissible to assume *a priori* that the crust of the planet does not have a relative motion. A thin crust composed of the lightest materials after the stratification of the Earth started forming during the liquid state, grew till the depth of 2900 km was reached. It was subjected to many deformations. It is obvious that we must pose several quite different problems of the dynamics, corresponding to various properties of the crust, since its behavior during the first and the latest geological periods could be quite different. Thus we shall have a clear general concept of the rotation of the Earth, if we succeed in solving a sequence of problems representing the gradual changes of the state of the whole Earth. As mentioned above the principal difficulty consists in the statement of the relative importance of different factors for the motion of the Earth at various geological periods.

Only during the last decennia the idea of the relative displacement of the Earth's crust became the object of mathematical investigations and the purpose of this paper is to establish to what degre the present state of those researches can explain the geophysical data.

Equations of the motion of the Earth relative to its center of mass--The first approximation in the theory of the Earth's rotation follows from the general equations of hydrodynamics, which we write in vector notation

$$\vec{a} = \vec{F} - (1/\rho)\,\text{grad}\,p + \nu\nabla^2\vec{v} \quad \dots\dots (1)$$

In case of a steady rigid-body rotation the equation of motion of an incompressible viscous liquid coincides with that of an ideal fluid. The equation of incompressibility is

$$\text{div}\,\vec{v} = 0 \quad \dots\dots (2)$$

But this kind of rotation is not the only one possible, even if we neglect the action of external forces. It is well known that a liquid mass may be in a state of zonal rotation (the ideal case) or in one more complicated. We can find the figure of a planet which corresponds to such a state. In the early history of the Earth, however, the steady rigid-body rotation or a zonal rotation should be subjected to some changes because there was influence of other bodies. The general problem of the Earth's rotation in a liquid state presents very great mathematical difficulties. But the present figure of the Earth differs but little from one corresponding to equilibrium. There have been but few tentative attempts to solve the problem of the motion of a liquid planet with a floating solid body. More advanced is the study of a planet with a rigid crust, which presents more interest for geological history. In this paper is considered a motion of a rigid body which has one or several cavities filled with a liquid. This problem was put in its general form by JOUKOWSKY [1885] and we shall write in vector notation the equations from which he started.

Let $\vec{\Omega}$ be the angular velocity of a particle of a liquid mass. Then curl $\vec{v} = 2\vec{\Omega}$. Taking (2) and the relation curl curl $\vec{v}$ = grad div $\vec{v} - \nabla^2\vec{v}$, into account we find

$$\nabla^2\vec{v} = -2\,\text{curl}\,\vec{\Omega} \quad \dots\dots (3)$$

The equations of Helmholtz follow from (1) in the case of an ideal fluid by forming the curl of all vectors in (1). We shall therefore have

$$\partial\vec{\Omega}/\partial t + (\vec{v}\cdot\nabla)\vec{\Omega} = d\vec{\Omega}/dt = (\vec{\Omega}\cdot\nabla)\vec{v} + (1/2)\,\text{curl}\,\vec{F} - (\nu/2)\,\text{curl}\,\nabla^2\vec{v},$$

if we suppose that ρ = const $\left\{\text{curl}\,[(1/\rho)\text{grad}\,p] = 0\right\}$. We find from (3) curl $\nabla^2\vec{v} = -2$ curl curl $\vec{\Omega}$. Putting

$$\text{curl}\,\vec{\Omega} = 2\vec{\Omega}_1\,,\ \text{curl}\,\vec{\Omega}_1 = 2\vec{\Omega}_2 \quad \dots\dots (4)$$

we obtain

$$d\vec{\Omega}/dt = (\vec{\Omega}\nabla)\vec{v} + (1/2)\,\text{curl}\,\vec{F} - 4\nu\vec{\Omega}_2 \quad \dots\dots (5)$$

In case of Newtonian gravitational forces it will be curl $\vec{F} = 0$. Bearing in mind, that curl $[\vec{v}\times\vec{\Omega}] = \nabla\times[\vec{v}\times\vec{\Omega}] = \vec{v}(\nabla\cdot\vec{\Omega}) + (\vec{\Omega}\cdot\nabla)\vec{v} - \vec{\Omega}(\nabla\cdot\vec{v}) - (\vec{v}\cdot\nabla)\vec{\Omega} = (\vec{\Omega}\cdot\nabla)\vec{v} - (\vec{v}\cdot\nabla)\vec{\Omega}$, $(\nabla\cdot\vec{v}) = 0$, $(\nabla\cdot\vec{\Omega}) = (1/2)$ div curl $\vec{v} = 0$, we find that (5) reduces to

$$\partial\vec{\Omega}/\partial t = \text{curl}[\vec{v}\times\vec{\Omega}] - 4\nu\vec{\Omega}_2 \quad \dots\dots (6)$$

This equation holds for every part of the Earth, which behaves like a viscous liquid, such as the core and the hydrosphere. The external forces are eliminated and we must take into account only th initial and boundary conditions for every liquid part of the Earth. The kinematic coefficient of viscosity can have different values in various regions. If we consider the early geological periods, during which there were floating bodies (continents) on the liquid Earth, we must write corresponding equations of the rigid dynamics. As mentioned above, this problem is too complicated and we must pass to other periods, for which the case of a solid crust will be a good approximation. We obtain the equations of the motion of the crust from the principle of moment of momentum $d\vec{G}/dt = \vec{L}$. If $\vec{G}'$ and $\vec{G}''$ are angular momenta of the crust and of the liquid core respectively, then $\vec{G} = \vec{G}' + \vec{G}''$, and we have

$$d\vec{G}'/dt + d\vec{G}''/dt = \vec{L} \qquad (7)$$

or three corresponding scalar equations, whose form depends on the choice of the axes of coordinates.

We shall consider the motion of the Earth about its center of mass under no forces ($\vec{L} = 0$) and, therefore, can integrate (7), thus

$$\vec{G}' + \vec{G}'' = \vec{G}_0 = \text{const.} \qquad (8)$$

The vectors $\vec{G}'$, $\vec{G}''$ are the momenta of the so-called equivalent solids of the crust and core respectively if we consider both parts of the Earth as deformable. The motion of each of these equivalent solids can be represented by an angular velocity vector, say $\vec{\Omega}^s$ and $\vec{\Omega}^c$. If we introduce these vectors into expressions for $\vec{G}'$ or $\vec{G}''$, we mean then the equivalent solids but not the real distribution of velocities in the corresponding part of the Earth. This distribution may be quite different from that one of a rigid body. Moreover, the kinetic energy of the equivalent solid may differ from that of a corresponding deformable body. On neglecting this very important circumstance one may be led to conclusions about the motion of a rigid body equivalent to a deformable system only at a given moment. It is necessary to bear in mind that the equivalent solid may also vary and that such a solution will not correspond to a posed problem. (For example, it is sometimes assumed that the Earth is composed of a liquid or plastic core and solid crust, which may be deformable. But it will be supposed that the motion of the system is represented by a single angular velocity and the equations derived from the form of kinetic energy, which holds for the equivalent solid at a given moment. The three equations obtained correspond naturally to the motion of this solid and it follows a periodical solution [PREY, 1940].) This is perhaps the principal difficulty concerning the problem of the Earth's rotation during the geological periods.

Assuming that the Earth's crust is rigid we have intermediate conditions concerning the behavior of the core only. But we may suppose that $\vec{G}''$ in (8) signifies the angular moment of the equivalent solid of the core, if we want to find the motion of the crust. In case of internal motion (6) and (8) yield a system of simultaneous equations, to which the boundary conditions must be added. If the internal motion is known we can find the angular momentum of the core $\vec{G}''$ and from (8) the vector $\vec{G}'$.

We write now the condition on the boundary of the core in a simplified form. Assuming that the friction at every point of the boundary surface of the core acts on the crust in the direction of the relative velocity v_r and is balanced by the internal friction of the liquid core, we shall have in the most simple case

$$\tau v_r = \mu \partial v_r/\partial n$$

where τ is the coefficient of the external friction and μ the coefficient of viscosity. Putting $\tau/\mu = \sigma$, we find the first boundary condition

$$\partial v_r/\partial n = \sigma v_r \qquad (9)$$

The second condition is that the normal velocity components are equal on both sides of the boundary surface. It is obvious that such conditions are necessary for the solution of a mechanical problem but can hardly correspond to the real circumstances in the Earth's interior, where a quasi-rigid state can change to a quasi-liquid one. There need not be either a quite definite surface of sliding of the crust or a definite boundary. Moreover, the internal movement in the core causes displacements in the solidifying outer shell of the planet. But in the problem of rotation of the Earth such changes are usually neglected without estimation of their order of magnitude.

In the general problem of rotation of a rigid body, having cavities filled with a liquid, various forms of the cavities have been considered (cylindrical, ellipsoidal, or spherical), [JOUKOWSKY, 1885; STEKLOFF, 1909; VOLTERRA, 1902; and others]. It was shown that various kinds of motion of the liquid are possible, the simplest one being the rigid-body rotation of the whole system. We shall note here some other general results of these investigations, which may be useful in understanding the Earth's rotation.

The motion of a homogeneous liquid in an ellipsoidal cavity may be an elliptic rotation, whose axis will describe a cone in absolute space. The rigid envelope will rotate faster than the liquid. The rotating liquid mass in the interior of a rigid body acts on it as a gyroscope. Currents in meridian planes are also possible. If the mean square of the angular velocity increases from the center toward the surface, the liquid will flow from the pole to the equator, and in the opposite direction in the case of a decreasing angular velocity. Some of these theoretical results of Joukowsky were proved by his experiments. Stekloff applied the method of successive approximations and stated the conditions of existence of integrals in the case of an ellipsoidal cavity. He has shown that periodical solutions are possible, if both the cavity and the ellipsoid of inertia are ellipsoids of revolution. Moreover, an ideal liquid in a spherical cavity has no influence on the motion of a rigid shell. In the case of a viscous fluid a steady motion is possible only if the whole system rotates like a rigid body.

Taking into account these simplest theoretical representations of the Earth's rotation, it may be expected that the real rotation ought to be more complicated than those given in the early attempts at its explanation.

Equations of the internal motion--After formation of a thin crust the movements in the Earth's interior depended at first on the initial state of the liquid core. We can suppose that the motion of the liquid in the early geological periods was an ordered one and corresponding to one of the possible distributions of velocities known from the theory of rotation of an isolated liquid mass [WASIUTYNSKI, 1946]. But there was also the influence of the external forces acting on the whole Earth, of the form of the core's boundary, of the bending of the crust, of the behavior of the material and, perhaps, of some other factors.

We shall write at first the general equations corresponding to (6) in curvilinear coordinates and then make some assumptions simplifying the problem. If we introduce some generalised orthogonal coordinates q_1, q_2, q_3 the line element may be written in the form

$$ds^2 = S_1{}^2 dq_1{}^2 + S_2{}^2 dq_2{}^2 + S_3{}^2 dq_3{}^2 \quad \ldots\ldots\ldots\ldots (10)$$

It is

$$\operatorname{div} \vec{v} = [\partial(v_1 S_2 S_3)/\partial q_1 + \partial(v_2 S_3 S_1)/\partial q_2 + \partial(v_3 S_1 S_2)/\partial q_3]/S_1 S_2 S_3 \quad \ldots\ldots (11)$$

and

$$\begin{aligned}\operatorname{curl} \vec{v} = \vec{q}_1[\partial(S_3 v_3)/\partial q_2 - \partial(S_2 v_2)/\partial q_3]/S_2 S_3 + \vec{q}_2[\partial(S_1 v_1)/\partial q_3 - \\ \partial(S_3 v_3)/\partial q_1]/S_3 S_1 + \vec{q}_3[\partial(S_2 v_2)/\partial q_1 - \partial(S_1 v_1)/\partial q_2]/S_1 S_2 \quad \ldots\ldots (12)\end{aligned}$$

$\vec{q}_i$ is the unity vector of the axes of curvilinear coordinates.

These formulas enable us to write three scalar equations corresponding to (6)

$$\partial\vec{\Omega}/\partial t = \operatorname{curl}[\vec{v} \times \vec{\Omega}] - 4\nu\vec{\Omega}_2 .$$

If ω_i denote the coordinates of $\vec{\Omega}$, we obtain these coordinates from (12), because $\operatorname{curl} \vec{v} = 2\vec{\Omega}$. It is, for example,

$$\omega_3 = [\partial(S_2 v_2)/\partial q_1 - \partial(S_1 v_1)/\partial q_2]/2S_1 S_2 \quad \ldots\ldots\ldots\ldots (13)$$

Then, by the equations (4)

$$2\vec{\Omega}_1 = \operatorname{curl} \vec{\Omega} = \vec{q}_1[\partial(S_3\omega_3)/\partial q_2 - \partial(S_2\omega_2)/\partial q_3]/S_2 S_3 + \ldots\ldots\ldots\ldots (14)$$

Hence

$$\omega_{11} = [\partial(S_3\omega_3)/\partial q_2 - \partial(S_2\omega_2)/\partial q_3]/2S_2 S_3,\ \omega_{12} = \ldots\ldots,\ \omega_{13} = \ldots\ldots\ldots (15)$$

are the coordinates of the vector $\vec{\Omega}_1$ and

$$2\vec{\Omega}_2 = \operatorname{curl}\vec{\Omega}_1 = q_1[\partial(S_3\omega_{13})/\partial q_2 - \partial(S_2\omega_{12})/\partial q_3]/S_2 S_3 + \ldots\ldots\ldots\ldots (16)$$

It is

$$[\vec{v} \times \vec{\Omega}] = (v_2\omega_3 - v_3\omega_2)\vec{q}_1 + (v_3\omega_1 - v_1\omega_3)\vec{q}_2 + (v_1\omega_2 - v_2\omega_1)\vec{q}_3 \quad \ldots\ldots (17)$$

and by equation (12)

$$\mathrm{curl}\,[\vec{v} \times \vec{\Omega}] = \vec{q}_1 \left\{ \partial[S_3(v_1\omega_2 - v_2\omega_1)]/\partial q_2 - \partial[S_2(v_3\omega_1 - v_1\omega_3)]/\partial q_3 \right\} S_2S_3 + \ldots \qquad ..(18)$$

Inserting (18), (16) and (15) in (6) we obtain

$$\left.\begin{aligned}
\partial\omega_1/\partial t = & \left\{\partial[S_3(v_1\omega_2 - v_2\omega_1)/\partial q_2 - \partial[S_2(v_3\omega_1 - v_1\omega_3)]/\partial q_3\right\}/S_2S_3 - \\
& \nu\Big(\partial\left\{S_3[\partial(S_2\omega_2)/\partial q_1 - \partial(S_1\omega_1)/\partial q_2]/S_1S_2\right\}/\partial q_2 - \partial\Big\{S_2[\partial(S_1\omega_1)/\partial q_3 - \\
& \qquad \partial(S_3\omega_3)/\partial q_1]/S_3S_1\Big\}/\partial q_3\Big)/S_2S_3 \\
& \partial\omega_2/\partial t = \ldots\ldots \\
\partial\omega_3/\partial t = & \left\{\partial[S_2(v_3\omega_1 - v_1\omega_3)]/\partial q_1 - \partial[S_1(v_2\omega_3 - v_3\omega_2)]/\partial q_2\right\}/S_1S_2 - \\
& \nu\Big(\partial\left\{S_2[\partial(S_1\omega_1)/\partial q_3 - \partial(S_3\omega_3)/\partial q_1]/S_3S_1\right\}/\partial q_1 - \partial\Big\{S_1[\partial(S_3\omega_3)/\partial q_2 - \\
& \qquad \partial(S_2\omega_2)/\partial q_3]/S_2S_3\Big\}/\partial q_2\Big)/S_1S_2
\end{aligned}\right\} \ldots . (19)$$

These general equations hold for every motion of a viscous liquid. But it is important for an explanation of the Earth's evolution to consider some simple kinds of internal movements. We will now, therefore, clear up the conditions and kind of some "regular" movements.

(1) If we assume, that v_3, S_1 and S_3 do not depend from the coordinate q_3, the equation of continuity reduces to

$$\mathrm{div}\,\vec{v} = [\partial(v_1S_2S_3)/\partial q_1 + \partial(v_2S_3S_1)/\partial q_2]/S_1S_2S_3 = 0 \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

Then it is possible to define a "stream" function $x(q_1, q_2, t)$ on putting

$$S_2S_3v_1 = \partial\psi/\partial q_2\ , \ S_3S_1v_2 = -\,\partial\psi/\partial q_1 \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

The quantity (13) may be then written in the form

$$\omega_3 = -\left\{\partial[(S_2/S_3S_1)(\partial\psi/\partial q_1)]/\partial q_1 + \partial[(S_1/S_2S_3)(\partial\psi/\partial q_2)]/\partial q_2\right\}/2S_1S_2 \ldots . (22)$$

In a recent paper BONDI and LYTTLETON [1948] introduced the operator

$$D^2 = (S_3/S_1S_2)\left\{\partial[(S_2/S_3S_1)(\partial/\partial q_1)]/\partial q_1 + \partial[(S_1/S_2S_3)(\partial/\partial q_2)]/\partial q_2\right\} \ldots\ldots\ldots (23)$$

We have therefore

$$\omega_3 = -D^2\psi/2S_3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (24)$$

(2) If the quantities ω_1, ω_2, S_1, S_2 do not also depend on q_3 the first and third of Eq. (19) reduce to

$$\left.\begin{aligned}
\partial\omega_1/\partial t = & \Big(\partial[S_3(v_1\omega_2 - v_2\omega_1)]/\partial q_2 - (\nu/S_2S_3)\,\partial\Big\{S_3[\partial(S_2\omega_2)/\partial q_1 - \\
& \qquad \partial(S_1\omega_1)/\partial q_2]/S_1S_2\Big\}/\partial q_2\Big)/S_2S_3 \\
\partial\omega_3/\partial t = & \left\{\partial[S_2(v_3\omega_1 - v_1\omega_3)]/\partial q_1 - \partial[S_1(v_2\omega_3 - v_3\omega_2)]/\partial q_2\right\}/S_1S_2 \\
& + (\nu/S_1S_2)\left\{[\partial(S_2/S_3S_1)/\partial q_1][\partial(S_3\omega_3)/\partial q_1] + [\partial(S_1/S_2S_3)/\partial q_2]\,[\partial(S_3\omega_3)/\partial q_2]\right\}
\end{aligned}\right\} .(25)$$

The sum in the last braces by (23) and (24) is

$$-\,(S_1S_2/2S_3)D^2D^2\psi = -(S_1S_2/2\,S_3)D^4\psi$$

We obtain from (12)

$$\omega_1 = [\partial(S_3v_3)/\partial q_2]/2S_2S_3, \omega_2 = -[\partial(S_3v_3)/\partial q_1]/2S_3S_1 \ldots\ldots\ldots\ldots\ldots\ldots (26)$$

On writing $S_3v_3 = \chi$, the left side of the first of (25) becomes

$$\partial\omega_1/\partial t = [\partial(\partial\chi/\partial t)/\partial q_2]/2S_2S_3$$

Inserting the above values of ω_1 and ω_2 in the right side of (25) and multiplying by $2S_2S_3$ we can integrate this equation. It will be

$$\partial\chi/\partial t - [\partial(\psi,\chi)/\partial(q_1,q_2)]/S_1S_2S_3 = \nu D^2\chi \quad \ldots\ldots \quad (27)$$

By similar transformation the third of (25) reduces to

$$\partial(D^2\psi)/\partial t - (2\chi/S_1S_2S_3^2)\partial(S_3,\chi)/\partial(q_1,q_2) - (2D^2\psi/S_1S_2S_3^2)$$

$$[\partial(S_3,\psi)/\partial(q_1,q_2)] + (1/S_1S_2S_3)[\partial(D^2\psi,\psi)/\partial(q_1,q_2)] = \nu D^4\chi \quad \ldots\ldots \quad (28)$$

Since we consider a special kind of motion, and all the velocities depend on two functions ψ and χ, which satisfy the equations (27) and (28), we do not need the second equation (19). These equations were reduced by Bondi and Lyttleton to a linear form in the case of cylindrical coordinates under following conditions. (This form must not be associated with the special problem of the action of tidal forces considered by these writers.)

(3) The function ψ and its derivatives are small quantities and their products may be neglected. This assumption does not mean that a movement of the liquid differs slightly from a rigid-body rotation, because great differences may exist between the velocity components in the planes perpendicular to the axis of rotation.

In case of cylindrical coordinates: $q_1 = z$, $q_2 = r$, $q_3 = \gamma$ we have $ds^2 = dz^2 + dr^2 + r^2d\gamma^2$, $S_1 = S_2 = 1$, $S_3 = r$ and from (13)

$$D^2 = \partial^2/\partial z^2 + \partial^2/\partial r^2 - (1/r)\partial/\partial r \equiv \partial^2/\partial z^2 + r(\partial/\partial r)(1/r)(\partial/\partial r) \quad \ldots\ldots \quad (29)$$

Putting $\rho = r^2$ we obtain

$$D^2 = \partial^2/\partial z^2 + 4\rho\ (\partial^2/\partial\rho^2) \quad \ldots\ldots \quad (29')$$

Only the functional determinants in (18) and (19)

$$\partial(r,\chi)/\partial(z,r) = -\partial\chi/\partial z \quad , \quad \partial(\psi,\chi)/\partial(z,r) = (\partial\psi/\partial z)(\partial\chi/\partial r) - (\partial\psi/\partial r)(\partial\chi/\partial z)$$

will be linear in ψ and its derivatives. These equations reduce, therefore, to

$$\left.\begin{aligned} &(\partial/\partial t - \nu D^2)\chi - (1/r)[(\partial\psi/\partial z)(\partial\chi/\partial r) - (\partial\psi/\partial r)(\partial\chi/\partial z)] = 0 \\ &(\partial/\partial t - \nu D^2)D^2\psi + (2\chi/r^2)(\partial\chi/\partial z) = 0 \end{aligned}\right\} \quad \ldots\ldots \quad (30)$$

(4) If we assume, that the motion of the liquid mass differs slightly from a rigid-body rotation about a fixed axis (z), and put

$$\chi = (n + kt)r^2 + \phi(r^2,z) \quad \ldots\ldots \quad (31)$$

where n and k are two constants (author's notation, not Bondi and Lyttleton) and ϕ a small quantity of the order of ψ, we can neglect the products $(\partial\psi/\partial r)(\partial\chi/\partial z) = (\partial\psi/\partial r)(\partial\phi/\partial z)$ and $\phi(\partial\phi/\partial z)$ in (30). On considering the action of tidal friction in the case of the Earth, Bondi and Lyttleton assume that n is a small quantity and $k < 0$ is such, that $|k| << n^2$. We can adopt this hypothesis independently of the assumptions of the causes of this kind of motion and neglect the term having a factor kt. Equations (30) become

$$\left.\begin{aligned} &\nu D^2\chi + 2n\partial\psi/\partial z = kr^2 \\ &(\partial/\partial t - \nu D^2)D^2\psi + 2n\partial\phi/\partial z = 0 \end{aligned}\right\} \quad \ldots\ldots \quad (32)$$

The more general assumption $\chi = nr^2 + W(r^2,z,t)$ leads to the equations

$$\left.\begin{aligned} &(\partial/\partial t - \nu D^2)W - 2n\partial\psi/\partial z = 0 \ , \\ &(\partial/\partial t - \nu D^2)D^2\psi + 2n\partial W/\partial z = 0 \end{aligned}\right\} \quad \ldots\ldots \quad (32')$$

(5) Consider a very slow departure from rigid-body rotation. Then k will be very small and we may assume, that ψ does not depend explicitly from t (or less restrictively, that $\partial(D^2\psi)/\partial t = 0$). Equations (32) become

$$\left.\begin{aligned} \nu D^2\phi + 2n\partial\psi/\partial z = kr^2 \\ \nu D^4\psi - 2n\partial\phi/\partial z = 0 \end{aligned}\right\} \quad \ldots\ldots (33)$$

Though the coefficient of viscosity varied in the interior of the Earth, these equations may perhaps give the principal outlines of the movements in the liquid core during the first geological periods. The crust being thin enough, the core could be in such quasi-steady rotation about a fixed axis for a long time.

We can now consider two limit cases, $\nu = 0$ and $\nu = \infty$. The corresponding equations follow then from (33)

$$\partial\phi/\partial z = 0 \quad , \quad \partial\psi/\partial z = kr^2/2n \quad \ldots\ldots (34)$$

or

$$D^4\psi = 0 \quad , \quad D^2\phi = 0 \quad \ldots\ldots (35)$$

We can also imagine an intermediate case, $\nu \gg n$, but if r is very great (and k perhaps not so small as in the case of the Earth) ν may not be $\gg kr^2$. Then

$$D^4\psi = 0 \quad , \quad \nu D^2\phi = kr^2 \quad \ldots\ldots (36)$$

A solution of (34) is

$$\phi = \phi(r^2) \quad , \quad \psi = k\, r^2 z/2n \quad \ldots\ldots (37)$$

if the equatorial plane is the plane of symmetry. This solution is considered by Bondi and Lyttleton as one representing the motion in the interior of a liquid core. They assume also that there is between this part of the Earth's interior and the spherical boundary of the core, a layer in which the effect of viscosity is of prime importance. That is a modification of the problem, because we have posed the equations for the case of a homogeneous liquid. A restriction introduced by these writers, namely, that the changes of any entity in a given depth of the boundary layer are much greater than the changes parallel to the layer, can remove us from an other case, which is more important for the hypothesis of the zonal rotation of the Earth [JARDETZKY, 1935, 1948a and b]. (The above restriction gives, however, the possibility of finding a solution of the equations (33) in an explicit form satisfying the boundary conditions $\psi = \phi = 0$, $\partial\psi/\partial R = 0$ for $R = a$ (radius of the core). W in (32′) reduces then to kr^2t at the boundary and k can represent the secular retardation of the Earth (the change of rotation of the crust due to the tidal forces).

The other limit case ($\nu \rightarrow \infty$) is represented by the solution of equations (35). The functions (37) will also satisfy the equations (35), which may be written in the form

$$\left.\begin{aligned} \partial^2\phi/\partial z^2 + 4\rho\,\partial^2\phi/\partial\rho^2 = 0 \quad , \\ (\partial^2/\partial z^2 + 4\rho\,\partial^2/\partial\rho^2)(\partial^2\psi/\partial z^2 + 4\rho\,\partial^2\psi/\partial\rho^2) = 0 \end{aligned}\right\} \quad \ldots\ldots (38)$$

if $\phi(r^2) = \phi(\rho) = A + Br^2$.

Putting

$$D^2\psi \equiv \partial^2\psi/\partial z^2 + 4\rho\,\partial^2\psi/\partial\rho^2 = \xi \quad \ldots\ldots (39)$$

the second equation (29) reduces to

$$D^2\xi = \partial^2\xi/\partial z^2 + 4\rho\,\partial^2\xi/\partial\rho^2 = 0 \quad \ldots\ldots (40)$$

A solution of this equation may be put in the form

$$\xi = \eta(\rho)\cdot\zeta(z) \quad \ldots\ldots (41)$$

Hence

$$(1/\zeta)d^2\zeta/dz^2 = -(4\rho/\eta)d^2\eta/d\rho^2 = -c = \text{const.}$$

and

$$d^2\zeta/dz^2 + c\zeta = 0 \quad , \quad d^2\eta/d\rho^2 - c\eta/4\rho = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (42)$$

The first equation is well known, the second is a special case of the equation $y'' = Ax^{\alpha}y$. The integration depends on the solution of an equation of Riccati type. The solution may be also written in a form given by Cayley [for example, see **KAMKE**, 1942, p. 401]. From (40) and (35) an expression similar to that found for ξ may be found also for ϕ. Then on inserting (41) in (39) we obtain a partial differential equation of the second order, which must be satisfied by ψ. Since we do not intend to apply these general formulas to the problem of rotation of the Earth, we shall not write them. There is a reason that decreases the practical value of such considerations. BONDI and LYTTLETON [1948, p. 353] found that the speed of circulation about the axis of rotation is of a higher order of magnitude than the speed of circulation in meridian planes. Some assumptions (on the dimension of the core, the viscosity, etc.) lead to a maximum value of approximately 2×10^{-6}cm/sec for the speed along a parallel, but only to 5×10^{-10}cm/sec for the velocity component in a meridian plane. In the present investigation we shall consider, therefore, only a simple solution of the first of (38). By (31) and by definition of the quantity $\chi = S_3v_3 = rv_3$, on introducing the function ϕ, we take into account the circulation about the axis, superposed on the general rigid-body rotation (the angular velocity being n or n + kt). The function ψ defined by (21) represents the motion in meridian planes.

An integral of (38) is given by the equation

$$\phi = A\rho z^2 + B\rho^2 + C\rho z + D\rho + Ez + F \quad \ldots\ldots\ldots\ldots \quad (43)$$

if B = - A/4 and A, . . . , F are constants.

The values of these constants may be chosen in the way to satisfy the following condition on the boundary of the core. The angular velocity of the liquid interior may be represented by a function

$$\Omega = \Omega(r^2, z^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (44)$$

if we neglect a very slow drift in meridian planes and suppose that the rotation of the liquid about the axis z is symmetrical in both hemispheres. Assume that the core is bounded by a spherical surface S of the radius R = a; then $z^2 + r^2 = a^2$ on this surface. Thus it will be ($r^2 = \rho$)

$$\Omega_s = \Omega(r^2, a^2 - r^2) = \Omega_s(r^2) \quad \ldots\ldots\ldots\ldots\ldots \quad (45)$$

As mentioned above, we have suggested the importance of the existence of such a distribution of the velocities on the inner side of the Earth's crust during its formation. The hypothesis of the zonal rotation of the Earth facilitates a simple explanation of the formation of continents and mountain building using a simple law

$$\Omega_s = \Omega_{so} + \lambda r^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (46)$$

where Ω_{so} is a constant and λ a parameter. Then $[v_3]_s = \Omega_s r$. It is therefore

$$[\chi]_s = [v_3 r]_s = \Omega_s r^2$$

In general Ω will be a function of the time. In (31) we will now neglect the term depending on time, because k is small. Thus $\chi = nr^2 + \phi$ and $\chi_s = (\Omega_{so} + \lambda r^2)r^2$. We may now assume that the angular velocity of the crust, if it rotates about the same axis (z), corresponds to a certain mean value of Ω, say $\Omega^s = \Omega_{so} + \lambda r_1^2$. There may be a small component of the angular velocity of the crust in a plane perpendicular to the axis, the value of which can vary during different geological periods, but we neglect here this component and its variations. The relative angular velocity is then

$$\Omega_{rel} = \Omega - \Omega^s = \phi/r^2 = n + \phi/r^2 - \Omega_{so} - \lambda {r_1}^2$$

Thus

$$\Omega_{so} = n - \lambda {r_1}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (47)$$

By (47), the following conditions must be satisfied on the surface S

$$\phi_s = (\Omega_{so} - n)r^2 + \lambda r^4 = Ar^2(a^2 - r^2) - Ar^4/4 + Cr^2\sqrt{a^2 - r^2} + Dr^2 + E\sqrt{a^2 - r^2} + F$$

Therefore

$$\lambda = -5A/4 \quad , \quad Aa^2 + D = \Omega_{so} - n \quad , \quad C = E = F = 0$$

and

$$\phi = \lambda r^2(r^2 - 4z^2 + 4a^2)/5 + (\Omega_{so} - n)r^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (48)$$

The second of (36) is a special case of (39) and can be satisfied by the (43). Writing

$$\nu\partial^2\phi/\partial z^2 + 4\nu\rho \quad \partial^2\phi/\partial\rho^2 = k\rho \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (49)$$

Eq. (43) reduces to

$$\phi = A\rho z^2 + (k/8\nu - A/4)\rho^2 + D\rho$$

Putting ϕ_s again equal to $(\Omega_{so} - n)r^2 + \lambda r^4$, we obtain

$$\phi = (3\kappa/4\nu + \lambda)r^4/5 - (k/2\nu + 4\lambda)r^2z^2/5 + [(k/2\nu + 4\lambda)a^2/5 + \Omega_{so} - n]r^2 \quad \ldots\ldots \quad (50)$$

The corresponding distribution of velocities depends now on the viscosity, but the changes of velocities for different times due to this factor are not foreseen by (50).

All solutions enumerated under this heading (Equations of the internal motion) are still too simple to explain the behavior of the Earth's crust other than rotation about the same axis. If we postulate any axially symmetrical movement of the spherical or ellipsoidal core, we exclude the possibility that a couple perpendicular to the axis of rotation will act on the crust. But it is at once obvious, that a couple of frictional (tangential) forces appears when the crust begins to glide on the core. It is also easy to see, that the external friction on the inner boundary of the crust tends to bring its rotation into equilibrium. The subcrustal zonal movements will accelerate the motion of the crust in one part, say in the equatorial region, but the currents under other parts (for example, in polar regions) having a less velocity will keep back the crust. The question arises whether in the past these frictional forces were once balanced and the corresponding couple about the axis of rotation could be equal to zero, for there were external forces acting on the Earth and other causes which hindered such a simple kind of rotation. The existence of the other causes of the rotation of the crust will be considered under the next heading. It must be noted in connection with the problem of internal movements, that besides the "regular" zonal rotation given by the above formulas or the circulation considered by Bondi and Lyttleton and others there were currents of another kind. Since the interior of the Earth could not be in a state of mechanical or radiative equilibrium, there were convection currents. These currents could perhaps cause some local formations in the outer shell of the Earth's crust to appear in an early stage, but no later when it became thick enough. It seems less probable that the currents of the Benard-Rayleigh or allied types have attributed to principal formations and markings on the Earth's surface, as is sometimes believed. The cellular forms can be hardly found in the general structure of the crust.

The following remark may perhaps contribute to the question of the importance of different kinds of motion. As mentioned above, the speed in meridian planes could be of the order 5×10^{-10} cm/sec. This leads to a displacement $5 \times 10^{-10} \times 3.2 \times 10^7 \times 30 \times 10^6 = 4.8$ km during last 30 million years (since the Tertiary). But the order of the speed along the parallels estimated by Bondi and Lyttleton is 7×10^{-6} cm/sec. We have adopted even a less one [JARDETZKY, 1948a]: 6×10^{-7} cm/sec. The resulting displacement is $6 \times 10^{-7} \times 3.2 \times 10^7 = 19$ cm/yr or 5700 km since the Tertiary. Consequently the effect of displacement along parallels was the principal one, and the more detailed study of meridional circulations will not offer great importance for geophysical problems. The structure of the Earth's outer shell bears evident traces of a general torsion in the equatorial direction.

The motion of the Earth's crust-- Let us now consider the equations of the crust's movement during geological periods. If we do not take into account the influence of other bodies, we have at first three fundamental relations following from the integral of moment of momentum (17)

$$G_i' + G_i'' = G_{oi} \quad , \quad i = 1,2,3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (51)$$

where G_i denote the projections on any axes of coordinates; G_i' are the components of the angular momentum of the rigid crust. $\vec{G}_o$ is a constant vector and we shall assume that $\vec{G}''$ is the angular momentum of an equivalent solid of the core. Then we can introduce two angular velocities $\vec{\Omega}^s$ and $\vec{\Omega}^c$, representing the rotation of the crust and of this equivalent solid respectively (the index c denotes the core, the index s crust or outer shell). We shall assume, moreover, that the boundary of the core is a sphere, the center of which C is the center of inertia of the liquid. WAVRE [1925] and BILIMOVITCH [1934] have considered the Earth as a system with six degrees of freedom consisting of a rigid crust and a rigid core. Let C_1 and 0 be the center of inertia of the crust and of the whole Earth respectively. The simplest assumption in the case which we consider is that 0 is a fixed point. If C_1 and C do not coincide with 0 they will rotate about this point. But all three points remain always on a straight line and the distances $C_1 0$ and 0C do not vary, if the crust is rigid. We can, therefore, imagine a system of axes 0123 rotating with the crust. Denoting the moments and products of inertia of the crust by I_k and Π_{kj} and assuming that the vectors $\vec{G}'$, $\vec{G}''$ and $\vec{G}_o$ are the moments about the point 0, we have

$$\left.\begin{aligned} G_1' &= I_1\Omega_1^s + \Pi_{12}\Omega_2^s + \Pi_{13}\Omega_3^s \\ G_2' &= \Pi_{12}\Omega_1^s + I_2\Omega_2^s + \Pi_{23}\Omega_3^s \\ G_3' &= \Pi_{13}\Omega_1^s + \Pi_{23}\Omega_2^s + I_3\Omega_3^s \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (52)$$

If I_o is the moment of inertia of the core, whose ellipsoid of inertia is supposed to be also a sphere, $I_o\Omega_i^c$ are the projections of the moment about its center C. From the well-known relations between the moments and products of inertia about two parallel axes (the second passing through the center of inertia)

$$I_u = I_{uc} + M\delta^2 \quad , \ \Pi_{uv} = \Pi_{uvc} + M(\vec{u}\cdot\vec{r}_c)(\vec{v}\cdot\vec{r}_c)$$

where δ is the distance between the axes, $\vec{r}_c$ the vector $\vec{0C}$, $\vec{u}$ and $\vec{v}$ the unity vectors and M the mass of a system, in case of the core, we obtain

$$I_1^c = I_o + M^c\delta_{11}^2 \quad , \ \Pi_{12}^c = \Pi_{12c} + M^c x_c y_c \ , \ \ldots\ldots\ldots\ldots$$

The central products of inertia $\Pi_{kjc} = 0$. Introducing the spherical coordinates we have $x_c = r_c \sin\theta_c \cos\psi_c$, $y_c = r_c \sin\theta_c \sin\psi_c$, $z_c = r_c \cos\theta_c$. Then

$$\Pi_{12}^c = M^c r_c^2 \sin^2\theta_c \cos\psi_c \sin\psi_c \quad , \ \Pi_{13}^c = M^c r_c^2 \sin\theta_c \cos\theta_c \cos\psi_c \quad ,$$

$$\Pi_{23}^c = M^c r_c^2 \sin\theta_c \cos\theta_c \sin\psi_c \quad ,$$

$$\delta_{11}^2 = r_c^2(1 - \sin^2\theta_c \cos^2\psi_c)\ , \ \delta_{22}^2 = r_c^2(1 - \sin^2\theta_c \sin^2\psi_c)\ , \ \delta_{33}^2 = r_c^2 \sin^2\theta_c$$

Let G_o be the scalar value of $\vec{G}_o$ and θ_o, ψ_o the angles corresponding to its direction. Then the above relations lead to the following form of (51)

$$\left.\begin{aligned} &I_1\Omega_1^s + \Pi_{12}\Omega_2^s + \Pi_{13}\Omega_3^s + (I_o + M\delta_{11}^2)\Omega_1^c + M^c r_c^2 \sin^2\theta_c \cos\psi_c \sin\psi_c \Omega_2^c \\ &\qquad + M^c r_c^2 \sin\theta_c \cos\theta_c \cos\psi_c\, \Omega_3^c = G_o \sin\theta_o \cos\psi_o \\ &\Pi_{12}\Omega_1^s + I_2\Omega_2^s + \Pi_{23}\Omega_3^s + M^c r_c^2 \sin\theta_c \cos\psi_c \sin\psi_c \Omega_1^c + (I_o + M^c\delta_{22}^2)\Omega_2^c \\ &\qquad + M^c r_c^2 \sin\theta_c \cos\theta_c \sin\psi_c \Omega_3^c = G_o \sin\theta_o \sin\psi_o \\ &\Pi_{13}\Omega_1^s + \Pi_{23}\Omega_2^s + I_2\Omega_3^s + M^c r_c^2 \sin\theta_c \cos\theta_c \cos\psi_c \Omega_1^c + M^c r_c^2 \sin\theta_c \cos\theta_c \sin\psi_c \Omega_2^c \\ &\qquad + (I_o + M^c\delta_{33}^2)\Omega_3^c = G_o \cos\theta_o) \end{aligned}\right\} (53)$$

The angles θ_o, ψ_o may be expressed in terms of three Eulerian angles defining the position of the axes 0123. The unknown quantities being Ω_i^s, Ω_i^c and r_c, θ_c, ψ_c, in general we still need six equations. But in the case of the Earth the problem may be simplified. There are following groups of quantities Ω_i^s and Ω_i^c; I, Π, and M; r_c and δ_{ii}; θ_o and ψ_o. Independent assumptions can be made about these groups and the exact forms of (53) reduced to approximative ones.

We first suppose that the condition $r_c \ll R$, where R is the radius of the core, held always for the distribution of masses in the Earth. Then the terms with the factor r_c^2 or δ_{ii}^2 may be as usually neglected. We assume consequently that the points C, 0, and C_1 coincide and write

$$\left.\begin{aligned} I_1\Omega_1^s + \Pi_{12}\Omega_2^s + \Pi_{13}\Omega_3^s + I_o\Omega_1^c &= G_o \sin\theta_o \cos\psi_o \\ \Pi_{12}\Omega_1^s + I_2\Omega_2^s + \Pi_{23}\Omega_3^s + I_o\Omega_2^c &= G_o \sin\theta_o \sin\psi_o \\ \Pi_{13}\Omega_1^s + \Pi_{23}\Omega_2^s + I_3\Omega_3^s + I_o\Omega_3^c &= G_o \cos\theta_o \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (54)$$

(The influence of these three centers of inertia not coinciding during the whole geological history remains an open question.)

In the early history of the Earth the moment of inertia of a thin crust was relatively small. As the crust became thicker, the differences $I_o - I_k$ diminished and there was an instant when I_k surpassed the moment of inertia of the core. If the core in the present state can still be considered as a liquid one, its moment of inertia I_o is smaller than I_k. But the products of inertia seem to be small during the whole evolution of the Earth. With a good approximation, the outer boundary of the crust is an ellipsoid of revolution and perhaps the inner boundary differs but little from a sphere, the ellipticity of the Earth being 1:297. We may therefore assume that the crust had this form but there were some irregularities in its outer shell. We know such irregularities probably exist to a depth 60 km. At the greater depth, matter seems to be stratified regularly. If the axes 0123 are axes of the geodetic ellipsoid, the products of inertia Π_{ik} are defined only by the asymmetrical distribution of masses in the thin outer shell. They are therefore much smaller quantities than I_k, but nevertheless the fact that they do not vanish is very important. We will not yet specify the distribution of masses in the outer shell.

The natural assumption about this distribution is that after the formation of the crust all the moments and products of inertia were such that $I_k \ll I_o$ and $\Pi_{kj} \ll I_o$. From the actual structure of the outer shell we may also conclude that Π_{kj} values are smaller than I_k values.

There is an open question concerning the position of the momentum $\vec{G}_o$. We do not know now what direction may be attributed to the axis of rotation of the Earth when it was a fluid body. We cannot say anything definite about the time when the axis began its precessional motion. But it seems natural to suppose that, if we leave out of consideration the influence of other bodies, the axis of rotation of the liquid Earth had the direction of the momentum $\vec{G}_o$, and during some time after the solidification of the outer shell an axis of symmetry still passed in the neighborhood of $\vec{G}_o$. Then we may put $\theta_o = 0$ and write (54) in the form

$$\left.\begin{aligned} I_1\Omega_1^s + \Pi_{12}\Omega_2^s + \Pi_{13}\Omega_3^s + I_o\Omega_1^c &= 0 \\ \Pi_{12}\Omega_1^s + I_2\Omega_2^s + \Pi_{23}\Omega_3^s + I_o\Omega_2^c &= 0 \\ \Pi_{13}\Omega_1^s + \Pi_{23}\Omega_2^s + I_3\Omega_3^s + I_o\Omega_3^c &= G_o \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (55)$$

The components Ω_i^s and Ω_i^c are unknown functions. Nevertheless we may consider that they are small quantities. Moreover, we can set $\Omega_3^s = \Omega_3^c = n = \text{const}$ and assume that $\Omega_{1,2} \ll n^2$.

If we can neglect the first two terms in the third of (55) it becomes

$$I_3\Omega_3^s + I_o\Omega_3^c = G_o \quad \ldots\ldots\ldots\ldots (56)$$

or

$$(I_3 + I_o)n = I^o\Omega^o = \text{const} \quad \ldots\ldots\ldots\ldots (56^1)$$

where Ω^o is the angular velocity of equivalent solid of the whole Earth and I^o its moment of inertia about the axis of $\vec{\Omega}^o$.

In general there are still three equations necessary, because (55) contains six unknown quantities. We may now write three dynamic equations either for the crust or for the core. Since the components Ω_i^s and Ω_i^c satisfy the simple relations (55), we prefer to write the dynamic equations for the core. The principle of angular momentum leads to equation $d\vec{G}''/dt = -\vec{L}$, where $\vec{L}$ is the momentum about the point 0 of all forces acting on the crust. We obtain three scalar equations on projecting these vectors on the axes 0123. The projection of the derivative of a vector on a moving axis is

$$(d\vec{G}/dt) \cdot \vec{i}) = d(\vec{G} \cdot \vec{i})/dt - (\vec{G} \cdot [\vec{\Omega} \times \vec{i}])$$

if $\vec{i}$ is the unity vector of this axis and $\vec{\Omega}$ the angular velocity of its rotation. Since $I_o\vec{\Omega}_i^c$ are the components of $\vec{G}$, and $\vec{\Omega} = \vec{\Omega}^s$, we obtain

$$\left.\begin{aligned} I_o\, d\Omega_1^c/dt - I_o(\Omega_2^c\Omega_3^s - \Omega_3^c\Omega_2^s) &= -L_1 \\ I_o\, d\Omega_2^c/dt - I_o(\Omega_3^c\Omega_1^s - \Omega_1^c\Omega_3^s) &= -L_2 \\ I_o\, d\Omega_3^c/dt - I_o(\Omega_1^c\Omega_2^s - \Omega_2^c\Omega_1^s) &= -L_3 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (57)$$

where L_i denotes the components of $\vec{L}$. These quantities are composed of momentum of attraction, of centrifugal forces, and forces acting on the inner boundary of the crust, namely, the pressure and the friction. It was assumed, that the points 0 and C coincide. The core being a homogeneous sphere or having a spherical stratification, its attraction is directed towards the center and gives no momentum about the point 0. If there are currents of the kind considered above, we may take into account only the frictional forces, because the moment of pressure on a spherical boundary vanishes. It remains also the momentum of centrifugal forces acting on the crust.

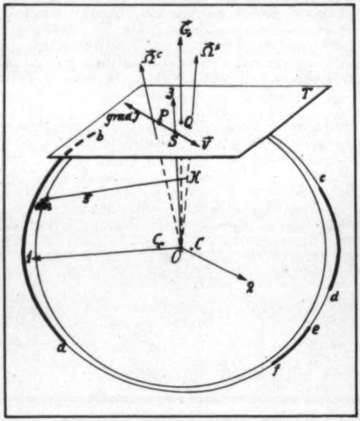

Fig. 1- Elements of the crustal problem

Let $\vec{s}(s_x, s_y, s_z)$ be the vector perpendicular to the axis of $\vec{\Omega}^s$ joining this axis with an element dm. The centrifugal force acting on dm is dm $\Omega^{s2}\vec{s}$ and the momentum about 0 is

$$\vec{N} = \int dm\, \Omega^{s2}[\vec{r} \times \vec{s}]$$

where $\vec{r}$ is the vector joining the point 0 and dm. Put $\vec{s} = \vec{r} - \overrightarrow{0K}$ (see Fig. 1). Then $s_x = x - (\overrightarrow{0K} \cdot \vec{1}) = x - \overline{0K} \cdot \Omega_1^s/\Omega^s$ and we have two similar expressions for s_y and s_z. In the system of reference 0123 the coordinates x, y, z of an element dm are constant, but the second term in s_x varies if the axis of instantaneous rotation of the crust changes its position in the body. It is supposed that $\vec{\Omega}^s$ will be in the neighborhood of the axis 3. In general this axis will not coincide with one of the principal axes of inertia, since we assumed that the distribution of masses in the outer shell is an asymmetrical one. Let all these axes lie close to one another. In case of a free motion $\vec{\Omega}^s$ would describe a conical surface about the principal axis of inertia. Then the term $\overline{0K} \cdot \Omega_1^s/\Omega^s$ would be a periodical one and we could consider x as a mean value of s_x during a period. The Eulerian nutation of the Earth is such a motion with a short period and is of no importance for the problems concerning geological periods. It is obvious that we do not yet know if there is a secular term in the expressions s_x, s_y, s_z, for such a term can arise when $\vec{\Omega}^s$ retires progressively from the principal axis of inertia.

On projecting $\vec{N}$ on the axes 0123, we obtain

$$\left.\begin{aligned} N_1 = \Omega^{s2}\int dm\,\vec{i}[\vec{r} \times \vec{s}] = -\Omega^{s2}\int dm\, z s_y &+ \Omega^{s2}\int dm\, y s_z \\ N_2 = -\Omega^{s2}\int dm\, x s_z &+ \Omega^{s2}\int dm\, z s_x \\ N_3 = -\Omega^{s2}\int dm\, y s_x &+ \Omega^{s2}\int dm\, x s_y \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (58)$$

Inserting the expressions $s_x = x - \overline{0K}\,\Omega_1^s/\Omega^s$, $s_y = y - \overline{0K}\,\Omega_2^s/\Omega^s$, $s_z = z - \overline{0K}\,\Omega_3^s/\Omega^s$, we obtain at first terms with the factors: $\int zy\,dm$, . . . , which are constant and, as we shall see, of the order of n^2. The remaining terms will be of a higher order. s_z oscillates nearly about its mean value 0, as it may be seen on Figure 1. Then

$$N_1 = \Omega^{s2}\Pi_{23} + \text{per. term} + \ldots,\ N_2 = -\Omega^{s2}\Pi_{13} + \ldots,\ N_3 = \text{per. term} + \ldots \quad \ldots (59)$$

If the crust has a structure like that mentioned above, the integrals in the products of inertia $\Pi_{23} = -\int zy\,dm$,. . . must be taken only over the asymmetrical part of the outer shell; for the symmetrical shells they will vanish. If we put $\Omega^{s2} = \Omega_1^{s2} + \Omega_2^{s2} + \Omega_3^{s2} \approx n^2$ and take the approximative mean values of (59), we obtain

$$N_1 = n^2\Pi_{23} \quad , \; N_2 = -n^2\Pi_{13} \quad , \; N_3 = 0 \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (60)$$

When the angle between the direction of $\vec{\Omega}^s$ and axis 3 is not very small, (60) may differ from (59) by terms of the same order.

Write now the expression representing the moment of the frictional forces acting on the boundary surface of the core. If there are currents which may be represented by an angular velocity $\vec{\Omega}(s^2,z^2)$ (see (44)), the relative velocity of a point at the inner boundary of the crust is given by equation $\vec{v}_r = (\vec{\Omega}^s - \vec{\Omega}) \times \vec{r}$. By Stokes's law the friction is a function of v_r and has the opposite direction or, if we take a linear function, it is equal to $-\tau\vec{v}_r$. Then the moment of these forces is represented by the vector $-\tau\int_s(\vec{r} \times \overline{v}_r)ds$, where the integral is taken over the whole boundary s. This moment could have a very great value and its action could be in the first period after formation of the crust very considerable. But we have suggested the importance of a zonal rotation of the Earth's interior and may conclude that there will be attained a state, by which the action of the relative currents in the equatorial zone will be balanced by the braking by polar currents, whose relative displacements have the opposite direction. Then the moment of frictional forces arising from the zonal currents ought to diminish and in an ideal case could vanish. We will not take into account, therefore, this moment, assuming that in the latter geological periods the motion of the crust was nearly balanced by currents in the core. But it is obvious that the moment of frictional forces will increase with every change of a balanced state and will oppose such a change. If the crust begins to glide on the core under action of some other causes, a new component of the moment will arise. Thus, the action of frictional forces may be very complicated. It seems, however, that it does not change in the last case the kind of the displacement of the crust but only its speed. We shall therefore, restrict our considerations to the case of the formulas (60).

We substitute in (57) $L_i = N_i$. There arises the question about the order of various terms in these equations. It was supposed that $\Omega_{1,2} \ll n^2$, n being a small quantity. Then the expression in the parentheses will be of an order $\ll n^3$. The quantities N_i are of the order n^2, but in case of the Earth the products of inertia were much smaller than I_o. It seems, nevertheless, more probable that the products $I_o\Omega_i^c\Omega_k^s$ may be neglected. Then (57) becomes

$$I_o \, d\Omega_1^c/dt = -N_1 \quad , \; I_o \, d\Omega_2^c/dt = -N_2 \quad , \; d\Omega_3^c/dt = 0 \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (61)$$

By (60) we obtain

$$\Omega_1^c = -(\Omega_{23}/I_o)n^2(t - t_o) \; , \; \Omega_2^c = (\Omega_{13}/I_o)n^2(t - t_o) \; , \; \Omega_3^c = n = \text{constant} \; . \; . \; . \; . \; . \; (62)$$

These relations hold, if the initial velocities $(\Omega_1^c)_o = (\Omega_2^c)_o = 0$. Inserting (62) in equations (55), we obtain

$$\left.\begin{aligned} I_1\Omega_1^s + \Pi_{12}\Omega_2^s + \Pi_{13}\Omega_3^s &= \Pi_{23}\, n^2(t - t_o) \\ \Pi_{12}\Omega_1^s + I_2\Omega_2^s + \Pi_{23}\Omega_3^s &= -\Pi_{13}\, n^2(t - t_o) \\ \Pi_{13}\Omega_1^s + \Pi_{23}\Omega_2^s + I_3\Omega_3^s &= -I_o n + G_o \end{aligned}\right\} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (63)$$

The components Ω_i^s of the angular velocity of the crust are solutions of this system of linear equations and may be written in the form

$$\Omega_1^s = D_1/D \quad , \; \Omega_2^s = D_2/D \quad , \; \Omega_3^s = D_3/D \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (64)$$

where the determinant D is a constant and D_i are linear functions of the time.

The most simple and, as it seems, the most important is the case when we can neglect the terms $\Pi_{ik}\Omega_j^s$ in (63). Instead of (64) we have then

$$\Omega_1^s = (\Pi_{23}/I_1)n^2(t - t_o) \; , \; \Omega_2^s = -(\Pi_{13}/I_2)n^2(t - t_o) \; , \; \Omega_3^s = n \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (65)$$

These values, as stated above, correspond to a mean angular velocity, its periodical changes due to the free nutation being excluded. Then the direction of the mean angular velocity will coincide with one of the principal axes of inertia of the crust. On Figure 1 let OP be a mean position of the axis of rotation. The point P is the mean pole of rotation and the pole of inertia. Let S be the pole of symmetry of the crust and T the tangent plane at this point. The investigations of MILANKOVITCH [1941] have shown the importance of geometrical representation of the motion of the Earth's pole. This representation is based on the notion of spherical field of inertia. To each direction passing through the point 0 there is a corresponding moment of inertia about this axis. If α, β, γ denote the cosines of the angles formed by this direction with the axes of coordinates, the moment of inertia of the whole Earth is

$$I = (I_1 + I_0)\alpha^2 + (I_2 + I_0)\beta^2 + (I_3 + I_0)\gamma^2 + 2\Pi_{23}\beta\gamma + 2\Pi_{31}\gamma\alpha + 2\Pi_{12}\alpha\beta \qquad (66)$$

This value may be associated with the point of intersection of the axis with the Earth's surface. We have then on this surface a field of the scalar I. The simplest assumption is that the surface of the Earth is a sphere. We may now consider a part of the field in the close neighborhood of the pole belonging to the tangent plane T. Putting $X = R_0\alpha$, $Y = R_0\beta$, $Z = R_0\gamma$, where R_0 is the radius of the sphere, we have $R_0^2 = X^2 + Y^2 + Z^2$ and find that

$$R_0^2 I = (I_1 + I_0)X^2 + (I_2 + I_0)Y^2 + (I_3 + I_0)(R_0^2 - X^2 - Y^2) + 2\Pi_{23}YR_0 + 2\Pi_{13}R_0X \qquad (67)$$

if X and Y are small quantities. We can calculate now the derivatives of I

$$\left.\begin{aligned} R_0^2\, \partial I/\partial X &= 2(I_1 - I_3)X + 2\Pi_{13}R_0 \\ R_0^2\, \partial I/\partial Y &= 2(I_2 - I_3)Y + 2\Pi_{23}R_0 \end{aligned}\right\} \qquad (68)$$

which at the pole of symmetry (X = Y = 0) have the values

$$(\partial I/\partial X)_{X=Y=0} = 2\Pi_{13}/R_0 \ , \ (\partial I/\partial Y)_{X=Y=0} = 2\Pi_{23}/R_0 \qquad (69)$$

Therewith the vector grad I is defined for each point of the small plane region. The point S of the crust's surface has the velocity $\bar{v}_s = [\vec{\Omega}^s \times R_0\vec{k}]$, where $\vec{k}$ denotes the unity vector of the axis 03. The components of this velocity are

$$v_{s1} = \Omega_2^s R_0 \ , \ v_{s2} = -\Omega_1^s R_0 \ , \ v_{s3} = 0 \qquad (70)$$

or, taking into account the expressions (65),

$$v_{s1} = -(\Pi_{13}R_0/I_2)n^2(t - t_0) \ , \ v_{s2} = -(\Pi_{23}R_0/I_1)n^2(t - t_0) \qquad (71)$$

We see that these components will be proportional to the projections of grad I at the point S, if $I_1 = I_2$. Then we can write

$$\vec{v}_s = \kappa \text{ grad } I \qquad (72)$$

where

$$\kappa = -(R_0^2/2I_1)n^2(t - t_0) \qquad (73)$$

It is easy to see that the gradient of the moment of inertia (I^s) of the crust has also the values defined by the relations (68). Moreover, the values of the derivatives (69) depend only on the products of inertia of the outer shell, which is supposed to be asymmetrical. Therefore, if we introduce the moment of inertia J of this shell, instead of (72) we may write

$$\vec{v}_s = \kappa \text{ grad } J = \kappa \text{ grad } I^s \qquad (74)$$

All three gradients have the same value at the point S. Eq. (74) represents the theorem of MILANKOVITCH [1934] in a form corresponding to our formulation of the problem. According to this theorem the progressive part of the displacement of the Earth's pole of reference has at each moment directio of the gradient of the moment of inertia J. (The velocity of this displacement is opposite to $\vec{v}_s$.) The so-called pole of the "geophysical ellipsoid of reference" of Milankovitch is identical with the pole of symmetry. Milankovitch has found (74) in two different ways. The first consideration is based on the hypothesis of a continuous adaption of the Earth to the figure of equilibrium corresponding to the instantaneous position of the axis of rotation. He postulates thereby that the velocity of the pole of reference is directed along the line joining the principal pole of inertia P and the pole of reference S. It may be also concluded from the existence of Polflucht forces acting on the continents, that (74) may hold. It is only necessary to assume that the secular angular velocity of the crust has the direction of this moment. Both investigations have a close connection with the hypothesis of isostasy, but Milankovitch has obtained for the coefficient κ two different expressions. These are certain constants. Assuming the Earth to be a system with six degrees of freedom, consisting on the rigid crust and rigid core as mentioned above, BILIMOVITCH [1933] is also led to a relation of the form (74). This relation holds for the initial motion of the system and the coefficient κ differs from those given by Milankovitch. Assuming the hypothesis on isostasy for the stratification in the outer shell of the crust, Bilimovitch has shown that the Polflucht forces act as the centrifugal forces in his model of the Earth. In the above considerations we followed an analogous method and obtained the equation (74), which holds for a mean velocity. It is obvious that the expression for the coefficient κ depends on the model adopted.

We have seen that some special assumptions ought to be used in order to derive (74). In a more general case, for example, in such as represented by formula (64) the motion will differ, however, from this kind of rotation. But, as it was shown by Milankovitch, the path of the Earth pole calculated on the basis of (74) agrees with the geophysical data. It is, therefore, important not only to establish, that such a motion of the Earth's crust is a possible one, among many others following from the dynamical equations, but also ascertain in exact way, which circumstances led to this case. (It is well known that some plausible assumptions led to other conclusions about the kind of rotation of the Earth's crust.)

As mentioned above, the first considerations about a secular motion of the Earth's crust were connected with the hypothesis of isostasy. Meanwhile an isostatic stratification in the outer shell of the Earth is not a necessary condition. It may be supposed, that there are regions of different densities (for example, thin spherical plates ab, cd, ef in Figure 1). Then the products of inertia Π_{jk} do not vanish. This circumstance is important. Thus we must consider the asymmetry of the distribution of masses in the crust as a first cause of its progressive motion (but not as a single one). Moreover, if the distribution of masses of the Earth corresponds more or less to the hypothesis of isostasy and there arise the Polflucht forces, an opposite case can also be imagined. Assume that in the homogeneous outer shell deeps form (ab, cd, ...,Figure 1) which are empty or filled up with a material in such a manner that their centers of inertia have lower positions than the primitive ones. The new moment will act in the opposite direction, but (74) will hold also in such a case. Essential are, therefore, the centrifugal forces and their existence must be considered as a second cause of the progressive motion of the crust. But both factors, asymmetry and centrifugal forces, act also in a material system when a problem of dynamics has a periodical solution. The frictional forces, could change a periodical motion to an aperiodical one. But we cannot yet conclude that the latter ought to exist during the whole geological history of the kind suggested by geophysical data. We must, therefore, give another explanation.

The expressions (62) and (65) are increasing functions of time. After a certain time interval their values will no more be of the order of n^2. They were, however, found from (57) under condition that $\Omega_{1,2} \ll n^2$. Moreover, if the axis 03 deviates from the direction of $\vec{G}_0$, (55) ceases to hold, for we can no more neglect the terms $\vec{G}_0 \sin \theta_0 \cos \psi_0$ and $\vec{G}_0 \sin \theta_0 \sin \psi_0$. If the crust were a rigid body having a spherical cavity and would move in a manner defined by (74) the pole of inertia P would wander with it and its distance from the fixed point Q would increase. We see that with this model we can not establish conditions favorable to the kind of motion foreseen by Milankovitch for a long time. During all geological periods the pole of inertia and the pole of rotation could remain close to the axis $\vec{G}_0$, if the crust were a deformable body. This assumption seems to be the most natural. Then the continuous adaptation to the figure of equilibrium corresponding to the new position of the axis of rotation is the factor which can provide that the motion of the Earth's crust will follow the law of Milankovitch during a very long time interval. Indeed, if we assume that the conditions after the formation of the thin crust correspond to those of Figure 1, the asymmetrical crust will be forced by the centrifugal forces to rotate about an axis in the equatorial plane. The pole of inertia P will be removed from the axis of rotation of the core, whose mass was the principal part of the Earth's mass. In order to simplify the problem we have supposed that the liquid core is a sphere. It should be an oblate spheroid and to tend to adopt an equilibrium figure corresponding to its axis of rotation produced by a new distribution of centrifugal forces. The adaptation began, therefore, after the first displacement. This was possible if the crust was able to bend. The flexibility of the Earth's crust was, therefore, a necessary condition that the pole of inertia of the whole Earth and the axis of symmetry 03, being removed, have again returned in the neighborhood of the point Q (see Figure 1). But this axis and the point P (belonging to the Earth's surface) have continuously changed their positions in the crust. For, in the next time interval, for which the conditions of applicability of the theorem of Milankovitch were reestablished, the crust could again be removed and this process may be repeated as long as the crust was flexible. It is essential for these considerations, that the increasing of the crust's thickness could not have great influence on the dynamical asymmetry of the outer shell. The solidification of the deeper shells has probably not produced any considerable changes of the stratification, for as it was established under the heading Equations of the internal motion, the currents in the core could be regular (those in meridian planes being without importance). The question arises whether mountain building or the displacements of continents could produce some considerable changes of the moments and products of inertia of the outer shell (especially of Π_{13} and

Π_{23} of (71) which define the velocity). It may be expected, however, that mountain building had but a little influence on the migration of the pole, for its path calculated by MILANKOVITCH [1941, p. 279] for the present distribution of continents with smoothed mountain ranges agrees with the principal part of the path given by Kreichgauer, Köppen, and Wegener. The calculated path is one of the orthogonal trajectories to the lines J = constant on the Earth's surface. The former join the points corresponding to the maximum and minimum-moments of inertia of the outer shell. It is important to notice that only the pole of inertia of the whole Earth must lie in the neighborhood of the axis of rotation of the core. The poles of inertia of the outer shell corresponding to its principal moments will move with the crust. If the relations (74) and (72) have held during the whole geological history, this progressive motion could cease only when $\vec{v}_s = 0$ or grad J = grad I = grad $I^s = 0$. That means that the poles of inertia of the crust and of whole Earth respectively must coincide.

From these considerations we may conclude:

(1) The progressive displacement of the Earth's crust during the geological periods is due to the simultaneous rotation about an axis in the equatorial plane, and adaptation.

(2) Its primary cause is the action of the moment of centrifugal forces arising from the asymmetrical distribution of masses in the outer shell.

(3) The adaptation was possible, because the crust was flexible and the core liquid (in the earlier geological periods, but for the latter periods the designation "fluidal" introduced by Milankovitch will perhaps better correspond to the state of the Earth's interior).

(4) The currents in the interior of the Earth have had but a little influence on the component of sliding of the crust, perpendicular to their axis.

As long as no action of the external forces is taken into account, the Earth's rotation in space ought to be of such a kind, that the instantaneous axis of rotation would be in the neighborhood of the initial moment of momentum $\vec{G}_0$, the region of Hawaii descending slowly to the equatorial plane of the core.

Milankovitch has given the values of the moments and products of inertia calculated for the present configuration of continents on the basis of the hypothesis of isostasy. These moments and the products of inertia Π_{13}, Π_{23} are of the order $8\pi C_2/3$ and $0.2 \times (C_1 - C_2)$, $C_1 = 4.5985 \times 10^{39}$, $C_2 = 5.1321 \times 10^{39}$ in CGS system. The coefficients of $(t - t_0)$ in the expressions (65) are, therefore, of the order $(\Pi_{23}/I_1)n^2 \approx (0.2 \times 0.5 \times 10^{39}/4 \times 10^{40})n^2 \approx n^2/400$. Thus, Ω_1^s and Ω_2^s being proportional to $t - t_0$ will satisfy the postulated conditions $\Omega_{1,2} \ll n^2$ only for a very short time. It must be remembered, however, that in fact these components remain still smaller, for the expressions (65) were calculated without taking into account the frictional forces. If we consider the real migration of the pole, an angular velocity of the order $n^2/400 = (7.292 \times 10^{-5})^2/400 \approx 1.4 \times 10^{-11}$ sec^{-1} is still too large. Since it is assumed that the Earth's pole has described nearly an eighth of a meridian since the Carboniferous (during the last 300 millions of years), the mean angular velocity of this rotation of the crust would correspond to period $T = 8 \times 300 \times 10^6$ yr $\approx 7.6 \times 10^{17}$ sec and would be of the order $2\pi : T \approx 0.8 \times 10^{-17}$ sec^{-1}. It seems probable that the frictional forces could reduce the values obtained above in a simplified problem to the order required by geophysical data.

Migration of the Earth's poles--There is an important question, in the amount the path of the pole could be changed by drift of continents. As answer can be given if we consider not only the present configuration of continents but also a single continent (the Pangea), whose area is equal to the sum of the areas of all present continents, and a situation intermediate between that and the existing configuration. Since the form and position of continents must also be taken into account, we shall make use of the map given by Wegener.

On integrating the (74) MILANKOVITCH [1941, p. 255] has found the family of spherical curves representing the possible paths of the Earth's poles. These curves are given by

$$\cos\Psi \tan^k\Psi = C_1 \tan\Phi \qquad (75)$$

where Φ and Ψ are spherical angles defined in a system of axes corresponding to the positions of the principal axes of inertia of the outer shell. The constant C_1 may be found by the present position of the pole and

$$k = (J_3 - J_1)/(J_2 - J_1) \qquad (76)$$

($J = \Omega$ in the notation of Milankovitch), J_1, J_2, J_3 being the principal moments of inertia of the outer shell. It is shown by Milankovitch that

$$J_k = 8\pi C_2/3 + (C_1 - C_2)a_k \qquad (77)$$

Assuming the hypothesis of isostasy, the constants C_1 and C_2 will depend on the density of the sima and sial, respectively, on the thickness of the isostatic layer formed by continents and ground of the ocean. But it is easily seen that the exponent k depends only on a_i

$$k = (a_3 - a_1)/(a_2 - a_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (76')$$

Since $C_1 a_k$, ($k = 1,2,3$) are the principal moments of inertia of the continents, the quantities a_k are given by formulas

$$\begin{aligned} a_k = {} & i_1 \cos^2 \phi_k \cos^2 \psi_k + i_2 \cos^2 \phi_k \sin^2 \psi_k + i_3 \sin^2 \phi_k - \lambda_1 \sin 2\phi_k \sin \psi_k - \\ & - \lambda_2 \sin 2\phi_k \cos \psi_k - \lambda_3 \cos^2 \phi_k \sin 2\psi_k \quad \ldots\ldots\ldots\ldots \quad (78) \end{aligned}$$

and we can now calculate the "moments (i_k) and products (λ_k) of inertia" about the axes of the present map (the first axis being in the meridian of Greenwich). (The notations of Milankovitch are $\lambda_1 = -\Pi_{23}$, $\lambda_2 = -\Pi_{13}$, $\lambda_3 = -\Pi_{12}$.) The angles ϕ_k, ψ_k ($k = 1,2,3$) will then define the positions of the principal axes of inertia of all continents. These angles are solutions of the system of equations

$$\left.\begin{aligned} \tan 2\phi &= (2\lambda_1 \sin \psi + 2\lambda_2 \cos \psi)/\left\{i_3 - (i_1 + i_2)/2 - [(i_1 - i_2)\cos 2\psi]/2 + \lambda_3 \sin 2\psi\right\} \\ \tan \phi &= [(i_1 - i_2)\sin 2\psi + 2\lambda_3 \cos 2\psi]/(2\lambda_2 \sin \psi - 2\lambda_1 \cos \psi) \end{aligned}\right\} \ldots .(79)$$

which will be obtained, if the extreme values of (78) will be determined by the conditions $\partial a/\partial \phi = 0$, $\partial a/\partial \phi = 0$.

It is, moreover, assumed that the areas of continents may be composed of several spherical quadrangles bounded by arcs of meridians and parallels. Then, the moments and products of inertia of such a homogeneous quadrangle ($\phi', \phi''; \psi', \psi''$) may be calculated by the formulas

$$\left.\begin{aligned} i_1 = (\Delta\psi/2 - K_2/4)D_1 + \Delta\psi D_2 \ , \ i_2 = (\Delta\psi/2 + K_2/4)D_1 + \Delta\psi D_2 \ , \ i_3 = \Delta\psi D_1 \\ \lambda_1 = K_3 D_3 \quad , \quad \lambda_2 = -K_1 D_3 \quad , \quad \lambda_3 = -K_4 D_1/4 \end{aligned}\right\} \ldots (80)$$

where $\Delta\psi = \psi'' - \psi'$ and

$$\left.\begin{aligned} K_1 = \sin \psi'' - \sin \psi' \ , \ K_2 = \sin 2\psi'' - \sin 2\psi' \\ K_3 = \cos \psi'' - \cos \psi' \ , \ K_4 = \cos 2\psi'' - \cos 2\psi' \\ D_1 = \sin \phi'' - \sin \phi' - (\sin^3 \phi'' - \sin^3 \phi')/3 \\ D_2 = (\sin^3 \phi'' - \sin^3 \phi')/3 \ , \ D_3 = (\cos^3 \phi'' - \cos^3 \phi')/3 \end{aligned}\right\} \ldots\ldots\ldots (81)$$

As far as the present positions are considered the quantities $i_1, \ldots, \lambda_3$ have the following values $i_1 = 3.70007$, $i_2 = 3.44170$, $i_3 = 3.03803$, $\lambda_1 = 0.19052$, $\lambda_2 = 0.24039$, $\lambda_3 = -0.00230$ calculated by Milankovitch. He assumed that the sialic crust is represented by spherical quadrangles as shown in Table 1.

Table 1--Spherical quadrangles representing the sialic crust (after Milankovitch)[a]

Item	I	II	III	IV	V	VI	VII	VIII	IX	X
	°	°	°	°	°	°	°	°	°	°
ψ''	160	150	45	150	100	150	120	160	160	160
ψ'	-20	-20	12	100	60	115	50	-20	-20	-20
ϕ''	90	60	0	0	-20	-20	-40	-60	80	-66.5
ϕ'	60	0	-30	-20	-40	-40	-60	-90	66.5	-80

[a] Some parts of continents (for example, America) are replaced by antipodical distribution, for such a displacement has no influence on the values of the moments of inertia.

We shall now represent the primary continent or the primary state of the sialic crust and an intermediate state by the systems of spherical quadrangles shown in Tables 2 and 3.

Table 2--Primary state

Item	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
	°	°	°	°	°	°	°	°	°	°	°
ψ''	350	80	100	120	140	160	160	160	160	160	80
ψ'	340	350	80	100	120	140	340	80	120	140	0
ϕ''	80	80	80	80	80	80	-60	-40	-20	-20	-60
ϕ'	-20	-60	0	0	30	60	-80	-60	-40	-20	-70

Table 3--Intermediate state

Item	I	II	III	IV	V	VI	VII	VIII
	°	°	°	°	°	°	°	°
ψ''	160	350	45	140	140	160	120	160
ψ'	340	340	12	120	80	80	340	340
ϕ''	90	0	0	0	-20	-40	-60	-50
ϕ'	0	-50	-30	-20	-40	-50	-90	-90

The corresponding values of $i_1, i_2, \ldots \lambda_3$, calculated by formulas (81) for the primary state are

$$i_1 = 3.61966, \; i_2 = 3.72993, \; i_3 = 3.03774,$$

$$\lambda_1 = -0.16825, \; \lambda_2 = 0.17995, \; \lambda_3 = 0.31820$$

For the intermediate state they are

$$i_1 = 3.66264, \; i_2 = 3.64467, \; i_3 = 3.11078,$$

$$\lambda_1 = 0.23963, \; \lambda_2 = 0.17232, \; \lambda_3 = -0.07013$$

We can now find by (79) the positions of the principal axes of inertia and by (78) the values of the principal moments of inertia. These values and the coordinates of the points of intersection of these axes with the Earth's surface are given in Table 4.

Table 4--Values of moments of inertia and coordinates of the northerly intersection of axes with the Earth's surface

Axis	State								
	Primary			Intermediate			Present[a]		
	J	Lat	Long	J	Lat	Long	J	Lat	Long
		°	°		°	°		° ′	° ′
a_1	2.977	76 N	32 W	2.993	68 N	58 E	2.899	65 16 N	49 34 E
a_2	3.354	4 N	139 W	3.587	3 N	42 W	3.491	13 55 N	72 56 W
a_3	4.056	14 N	131 E	3.840	22 N	133 W	3.790	20 02 N	168 08 W

[a] After Milankovitch

The moments of inertia of the outer shell J_k are sums of two terms $C_1 a_k$ (the moments of the continental plates) and those of the remaining part of the shell, namely, $(8\pi/3 - a_k)C_2$. In general we can imagine a distribution of matter in the outer shell corresponding either to $C_1 > C_2$ or $C_1 < C_2$. But in case of the Earth the latter inequality may be assumed, as was shown by Milankovitch. Then a maximum of J_k corresponds to a minimum of a_k, and inversely. It follows from the hypothesis of isostasy that $C_1 > C_2$, but this relation is not necessarily connected either with the correctness of this hypothesis or with the idea of floating continents.

We see from the data of Table 4, that the axis corresponding to the maximum moment of inertia J_1 intersect the Earth's surface not far from the present poles of rotation in all three states. The position of the axis of the minimum moment J_3 will, however, be changed far more by a displacement of continents. If the hypothesis of movements of continents relative to each other is correct the surface of the Earth caused a changing variable field of scalar J. It will be rather difficult to find the equation of the path of the Earth's pole in such a case, but we may proceed the inverse way. As mentioned above, Milankovitch has chosen as a starting point the present distribution of land and sea. Then for the corresponding constant field of the moments of inertia J the curve (1) representing the path is given by the present position of the North Pole. Accordingly, Milankovitch places the North Pole in the initial geological period not far from Hawaii, assuming that the axis of the minimum moment of inertia (20°N, 168°W) passed in the neighborhood of the axis of the Earth's rotation. The curve of Milankovitch (ab on Figure 2) represents very well the part of path from the present time back to the Carboniferous. The path of the North Pole given by Kreichgauer (de on Fig. 2) or Köppen and Wegener diverges, however, for the former geological periods from the theoretical path. It is generally considered that the part of the path given by Kreichgauer, which precedes the Carboniferous, [GUTENBERG, 1939, p. 193] is not correct. But at present we do not possess more precise data about the positions of the poles during these geological periods. According to Kreichgauer the North Pole in the Carboniferous should have the coordinates: 35°N, 147°W or, after Köppen and Wegener: 30°N, 145°W. In the Silurian the values are respectively: 0°, 123°W or 14°N, 123°W. The latter position of the pole lies too far from the curve of Milankovitch.

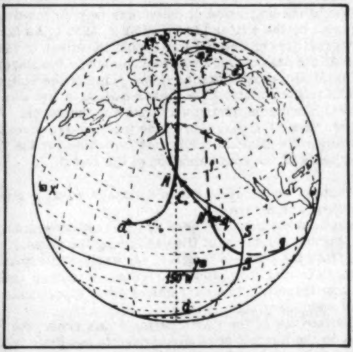

Figure 2--Suggested paths of the travel of the North Pole

We shall therefore make an attempt to reconstruct the path of the North Pole during the earlier geological periods. Our considerations will be based again on the theorem of Milankovitch and on the positions of the principal axes of inertia for two other states defined above.

If a single continent of the given shape existed in the primary state of the Earth's crust, its poles of inertia (x,y,z) had the coordinates (14°S, 49°W) (4°N, 139°W) and (76°N, 32°W). We see that the North Pole in the Silurian lies in the neighborhood of the pole y corresponding to minimum moment of inertia. In this region of the Earth's surface the possible paths of the Pole are represented by curve fg of Figure 2. Moreover, it follows from the theorem of Milankovitch that the movement of the North Pole ought to be directed toward point z, because this point corresponds to the maximum moment of inertia J_1. The end state would be reached if the pole of rotation would coincide with z. Taking into account the intermediate state with the poles of inertia q(22°N, 133°W), p(3°S, 138°E) and K(68°N, 58°E) and assuming that the pole of rotation after describing an arc SN comes in the neighborhood of q, we may conclude that this pole will move on a curve joining the points q and K. These points correspond to the new minimum and maximum moments of inertia respectively. One of the possible paths of the North Pole is represented by the curve NMK. It is obvious that this schematic representation by two arcs corresponding to the primary and intermediate state must be in fact replaced by a continuous change of the field of J. But, in spite of simplification of the problem, the part of the path preceding the Carboniferous agrees with that given by Kreichgauer. The upper parts of all three paths (NMK, ab, dc) lie close one to another. We may, therefore, suppose that, when the continents came to their present positions, the North Pole has passed from a curve joining the points q and K on the curve of Milankovitch. It must be also noticed that the latter represents an "undisturbed" movement of the North Pole [KÖPPEN, 1940].

If we take into account all three states, we shall also be led to come other conclusions. It is easily seen that in case of a single continental block the North Pole, if it were placed at the initial moment somewhere in the region gyf, ought to move toward the point z of the present polar region. There arises a very important question. After the rupture of the block, Eurasia, Africa and Australia were driven in an easterly direction [JARDETZKY, 1935, 1948 a and b]. The system of axes of coordinates used was referred to the meridian of Greenwich. It is, therefore, connected with Africa and moves with it in easterly direction. In this system of reference, America recedes in westerly direction and with it the pole of minimum moment, which has the longitudes 49°W, 133°W, 168°W in three states considered above. If we refer the positions of the pole of inertia to the axes connected with the block before its rupture, the points x,y and z must be displaced toward the west, because Eurasia and Africa must be close to America. The theoretical path will be placed, therefore, in this system of reference more toward the west. We may now conclude that the changes of position of the pole of minimum moment together with the displacement of the axes of reference can explain the fact that the lower part of the observed path of the pole is deflected in easterly direction (a westerly deflection of the path corresponds to the present position of continents).

We have chosen the Pole in the Silurian as an initial position and have seen that the arc SN agrees with the geophysical data. (It is not excluded that the North Pole before the Silurian was possibly even somewhat south of the present equator, because the plane xy is inclined to the latter.) To explain the path of the North Pole during this period and for a part of the Carboniferous the hypothesis of the rupture of the continental block is not yet necessary. But after these periods the present distribution of land and sea leads to a better correspondence of the theory and observation. It seems, perhaps, that this interpretation of the migration of the Earth's poles contradicts the assumption of Wegener that the movement of the continents began in the Cretaceous. On the other hand it has been suggested by many others that the spreading of continents might have occurred during some former periods. We restrict ourselves here only to a statement on the mechanism of processes in the Earth's crust and will not, therefore, make a more detailed discussion about the time scale or about the question of the movement of the pole of rotation during the periods preceding the Silurian.

The question now arises, how the interpretation of the migration of poles may be connected with the hypothesis of zonal rotation of the Earth suggested by the writer [JARDETZKY, 1935]. As far as the influence of other factors (for example, the external forces and the increasing thickness of the crust) is not taken into account, we can consider that the axis of the zonal movements in the Earth's interior has a fixed direction in space (say, for simplicity, perpendicular to the plane of the ecliptic). Now, if the North Pole were placed in the region SCM in the Pacific (that means that the crust was turned in space) and if there was a single continental block comprising all of the continents, its western boundary had nearly a meridional direction. Since the currents in the interior are directed along the parallels, there were during all periods since the Silurian conditions favorable for the rupture of the block in a manner foreseen by the hypothesis of the zonal rotation of the Earth.

Summary--(1) The liquid Earth was not in a state of equilibrium but in a state of zonal rotation similar to that observed at present on the Sun, Jupiter, and Saturn.

(2) This state was maintained after the formation of the crust. There are theoretically many possible types of currents in the Earth's interior, but the existence of the ones along the parallels, whose angular velocities increase under the crust from the poles to equator, can explain the spreading of continents and mountain building. The currents in meridian planes do not seem to have any important influence because their extraordinarily low velocity. The currents of other types could have some influence on various local formations of secondary signification.

(3) In case of the regular zonal currents in the interior of the Earth having a thin crust, the axis of rotation of a rigid body, which is equivalent to the Earth's core would deviate but little from its mean position. In the later periods this state could be changed primarily by the action of external forces.

(4) Besides some periodical movements, whose periods were relatively short, there was possible a slow secular displacement of the crust in space, which was progressive during all the geological periods.

(5) The sense of this rotation is defined by a theorem of Milankovitch. It seems that the conditions of applicability of this theorem were realized in the structure of the Earth's crust.

(6) The cause of the rotation of the crust is the existence of a moment of centrifugal forces acting on the crust and due to the asymmetry of the distribution of masses in the outer shell.

(7) The aperiodicity of this process is connected with the property of the whole Earth to tend to adopt a state of equilibrium corresponding to the position of the instantaneous axis of rotation. Owing to this circumstance the applicability of the theorem of Milankovitch is correct for the whole geological history.

(8) As it was shown by Milankovitch the calculated path of the North Pole since the Carboniferous to the present time agrees with the geophysical data, if the present distribution of continents is taken into account.

(9) An explanation of the shape of the path preceding the Carboniferous may be given (perhaps, also for some latter periods). This explanation is based on the distribution of masses in the uppermost layer of the crust corresponding to a single continental block and on the posterior movements of its parts relative to each other after the rupture.

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AIR FLOW OVER A MOUNTAIN BARRIER

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(Part 1 of this paper is condensed from a thesis submitted in partial fulfillment of the requirements for a degree of Master of Science at New York University)

Abstract--The flow of an incompressible and homogeneous (autobarotropic) atmosphere in a steady frictionless state is considered. In Part 1, the equations are set up for an air flow of finite width with fixed lateral boundaries. The final equation which is non-linear with non-constant coefficients is integrated by a graphical step by step procedure. The horizontal streamline pattern is obtained along with the pressure profile through the central portion of the field. A pressure trough is found to the lee of the mountain. In Part 2, the equations are set up for an air flow of infinite lateral extent. The final equation is integrated by a numerical step by step procedure. The position and the intensity of the lee pressure trough is found to depend on magnitude and direction of the initial air current and on the size and shape of the mountain. Finally using an idealized Rocky Mountain profile, the lee pressure trough is found to be in the vicinity of 90-100°W longitude depending on the initial wind velocity, which is in agreement with observational data.

Introduction

The general problem of air flow over mountain barriers has been given considerable attention. Such phenomena as foehn winds, "Moazagotl" type clouds, and the formation of troughs on the lee side of mountains have been regularly observed.

The most complete work on this problem of air flow over mountain barriers has been made by QUENEY [1947, 1948]. In the latter reference he gives a summary of all his previous studies. The basic method employed is that of stationary internal perturbations of a fluid with a stable continuous stratification. The perturbations are considered to be infinitesimal adiabatic disturbances on the given basic motion. Vertical cross sections of the stream flow pattern over typical mountain barriers and the ground level pressure profiles and ground level streamline pattern are given.

QUENEY [1948] states that in the case of a very broad mountain, the resulting pattern is one of stationary Rossby waves and that his theory gives a possible mechanism for the development of such long waves.

The purpose of the present paper is to set up the final differential equation for the air flow over an arbitrary mountain barrier directly from the equations of motion and continuity without resort to the perturbation theory. In order to integrate this equation it is necessary to use a step by step procedure. The relative effects on the resulting stream flow pattern and the pressure profile of variations of the magnitude and direction of the initial wind velocity and the size and shape of the mountain barrier will be shown.

Part 1--Flow of an air stream of finite width over a mountain

Theory--In developing the equations for an air stream of finite lateral width a homogeneous incompressible atmosphere of finite height is assumed. While the final equation cannot be integrated by the usual methods, it can be integrated by a graphical process. A horizontal stream flow pattern which is assumed to be invariant with height is obtained. In this method it is not necessary to be able to set up an analytical expression for the ground profile.

The atmosphere extends to a finite height H which may be expressed as $H = H(x,y)$ after a steady state is reached. A lower impermeable rigid surface is given by $G = G(x,y)$. It is only necessary that G be continuous and have continuous derivatives.

For this homogeneous incompressible atmosphere is a steady frictionless state, the equations of motion are

$$\left.\begin{aligned} u\,\partial u/\partial x + v\,\partial u/\partial y - \lambda v &= -(1/\rho)\,\partial p/\partial x = -g\,\partial H/\partial x \\ u\,\partial v/\partial x + v\,\partial v/\partial y + \lambda u &= -(1/\rho)\,\partial p/\partial y = -g\,\partial H/\partial y \end{aligned}\right\} \ldots\ldots\ldots\ldots (1)$$

where u and v are the horizontal components of velocity, λ is the Coriolis parameter, g is the acceleration due to gravity, and H is the height of the homogeneous incompressible atmosphere.

The equation of continuity is

$$\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0 \ldots\ldots\ldots (2)$$

Since u and v do not vary with height, (2) can be integrated from the ground surface G(x,y) to the top of the atmosphere H(x,y).

$$\partial(uD)/\partial x + \partial(vD)/\partial y = 0 \ldots\ldots\ldots (3)$$

where D = (H - G).

Equation (3) is completely satisfied by

$$Du = -\,\partial\psi/\partial y \text{ and } Dv = \partial\psi/\partial x \ldots\ldots\ldots (4)$$

Eliminate H from the equations of motion by a cross-differentiation process. Substitute the values of u and v from (4) and rearrange terms

$$(\partial\psi/\partial y)\,\partial\left\{\phi[\lambda + \partial(\phi\,\partial\psi/\partial x)/\partial x + \partial(\phi\,\partial\psi/\partial y)/\partial y]\right\}/\partial x$$
$$-\ (\partial\psi/\partial x)\,\partial\left\{\phi[\lambda + \partial(\phi\,\partial\psi/\partial x)/\partial x + \partial(\phi\,\partial\psi/\partial y)/\partial y\,]\right\}/\partial y = 0 \ldots\ldots (5)$$

where $\phi = 1/D$

Equation (5) is satisfied if and only if

$$\phi[\lambda + \partial(\phi\,\partial\psi/\partial x)/\partial x + \partial(\phi\,\partial\psi/\partial y)/\partial y] = F(\psi) \ldots\ldots\ldots (6)$$

Physically this equation states that the "absolute" vorticity of an individual element of the fluid is constant along any particular streamline.

Introducing natural coordinates, where the s and n axes are directed along and normal to the streamlines, (6) becomes

$$\phi[\lambda + K_s\phi\,\partial\psi/\partial n + \partial(\phi\,\partial\psi/\partial n)/\partial n] = F(\psi) \ldots\ldots\ldots (7)$$

where K_s is the curvature of the streamline.

In order to compute the second derivative term which appears in (7) it is necessary to impose vertical boundaries (β_1 and β_2) which contain the flow laterally (see Fig. 1). In solving the equations graphically, it is first necessary to substitute finite differences (Δ) for the infinitesimals (∂) in (4) and (7). This development is condensed from an unpublished report by Philip D. Thompson.

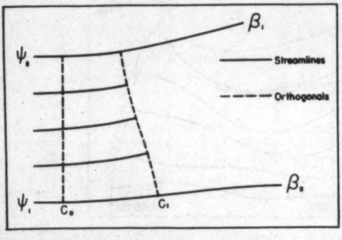

Fig. 1--Schematic streamlines and orthogonals

Procedure--To obtain the value of ϕ(or 1/D), H must be known at every point. For a reasonable approximation, H can be considered as constant and equal to the value in the undisturbed region. Certainly the greater portion of the variation in D arises from the variation in the ground profile (G).

A continuous sheet of graph paper (50 cm in width) is used for the construction work. The value of $\Delta\psi/\Delta n$ is obtained from (4) and the values of ψ_1 and ψ_2 are assigned at the boundaries. Nine equally spaced streamlines are marked in at the western edge of the mountain and these streamlines will have an easterly direction up to this point. A straight line orthogonal can be drawn at right angles to these streamlines. In order to avoid working with numbers of very large magnitudes, a new set of units is set up based on 10^4 sec as a time unit and 10^7 cm as a length unit.

At the first orthogonal, the values of K_s and $\Delta(\phi\Delta\psi/\Delta n)/\Delta n$ will be zero. From (7), the value of $F(\psi)$ for each streamline is equal to $\phi_0\lambda_0$. Thus the streamlines will continue in an easterly direction over the first interval. At the end of the first interval, the streamlines will still be equally spaced, but a different value of K_s is obtained for each streamline because of the different values of the Coriolis parameter. At the end of the second and subsequent intervals, all the terms in (7) will have to be computed to determine the curvature.

Along any orthogonal it is necessary to measure the distance between successive streamlines. From these distances $\Delta\psi/\Delta n$ and $\Delta(\phi\Delta\psi/\Delta n)/\Delta n$ can be computed. From the coordinates of the intersecting points (streamlines and orthogonal) the values of ϕ and λ can be determined. As the streamlines become more unevenly spaced, it will be necessary to construct smoothed orthogonals and the distances between streamlines will be measured along these smoothed lines.

In the construction of the proper curvatures, a large beam compass can be used to great advantage. Other geometrical artifices and construction aids are useful at all times in the work.

One of the main sources of error is the inaccuracy in the Δn measurements. These errors show primarily in the computation of the $\Delta(\phi\Delta\psi/\Delta n)/\Delta n$ term. Another source of error is in the actual construction of the orthogonals and the curved streamlines. The best method to check on these errors is a complete repetition of the entire work over certain portions of the stream flow pattern.

Over a portion of the work, the interval between successive orthogonals was reduced from 25 km to 12.5 km and the entire work repeated. No appreciable difference could be detected in this case. This serves as a check on the work and a justification of the size of the interval used.

Results--A mountain range two kilometers in height and 500 km across the base is assumed extending indefinitely in a north-south direction. Vertical boundaries extending west to east are set up at 35° and 45°N. This gives a stream flow approximately 1000 km in width. To simplify the computations of the ground profile, the height is assumed constant in the north-south direction and to be sinusoidal in the west-east direction. An initial current of ten meters per second is assumed blowing from the west.

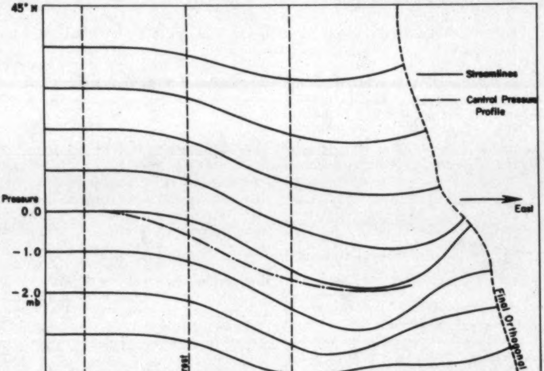

Fig. 2--Streamline pattern of airflow with fixed lateral boundaries across a north-south mountain of 500-km base and two-kilometer crest with an initial west wind of ten meters per second and pressure profile along central latitude line

The complete stream flow pattern is shown in Figure 2. The general pattern proves quite regular up to about 300 km beyond the eastern edge of the mountain. However, near the eastern edge of the mountain, a small irregularity can be seen in the southern-most streamline. This irregularity can be seen to repeat itself with increasing amplitude downwind along this streamline. Also this irregularity can be traced successively to the adjacent streamlines. It is believed that these irregularities are not real but are introduced because of the inability to smooth out irregularities in the computations of the $\Delta(\phi\ \Delta\psi/\Delta n)/\Delta n$ term near the boundary. A more accurate stream flow pattern might be obtained by smoothing the constructed streamlines.

Since the value of $\Delta\psi/\Delta n$ and ϕ can be determined at all points in the constructed streamline field, the values of u and v can be computed by means of (4). Using the first component of the equations of motion (1) the value of $\Delta p/\Delta x$ can be computed. From the values of $\Delta p/\Delta x$ the pressure profile in the x direction can be computed. The dashed line in Figure 2 shows the resulting decrease in pressure along a central latitude line compared with the adjacent streamlines. A pressure trough occurs at a distance of about 500 km from the crest (or 250 km beyond the eastern edge of the mountain).

Beyond $x = 900$ km the irregularities in the constructed streamline pattern become quite pronounced. Values of $\Delta\psi/\Delta n$ indicate velocities of the order of 100 m/sec at certain points. It is deemed inadvisable to continue to work beyond this point.

This method is quite general and is not too difficult to apply. It can be used for more complicated ground profiles since it is only necessary to know the actual elevations of all points in the field.

Part 2--Flow of an air stream of infinite width over a mountain

Theory--Again assuming a frictionless, steady state incompressible homogeneous atmosphere in which the horizontal components of the velocity remain constant in the vertical direction the equations of motion and continuity will be the same as in Part 1 (see (1) and (3)).

Cross differentiating the equations of motion in order to eliminate H, (1) reduces to the vorticity equation

$$u\,\partial\zeta/\partial x + v\,\partial(\zeta+\lambda)/\partial y + (\partial u/\partial x + \partial v/\partial y)(\zeta+\lambda) = 0 \;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\; (8)$$

where $\zeta = (\partial v/\partial x - \partial u/\partial y)$.

Assume that the air stream and the mountain extend an infinite extent in the north-south direction. It is also assumed that the variations in u and v in the y direction will be small in comparison to their variations in the x direction and can be neglected. Thus (8) becomes

$$u\,\partial^2 v/\partial x^2 + \beta v + (\partial v/\partial x + \lambda)\partial u/\partial x = 0 \;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;. (9)$$

Similarly, the equation of continuity reduces to

$$\partial(uD)/\partial x = 0 \;. (10)$$

The term $v\,\partial D/\partial y$ will be much smaller than $u\,\partial D/\partial x$ because of the fact that $\partial G/\partial y = 0$ and v is usually smaller than u.

Integrating (10) with respect to x

$$uD = \text{constant} = u_oD_o$$

$$u = u_oD_o/D \;. (11)$$

Also from (10)

$$\partial u/\partial x = -\,(u/D)\partial D/\partial x \;. (12)$$

Substituting (11) and (12) into (9), the basic equation becomes

$$\partial^2 v/\partial x^2 + (D/u_o D_o)\beta v - [(\partial v/\partial x + \lambda)/D]\partial D/\partial x = 0 \qquad (13)$$

Since this equation is non-linear and the coefficients are not constant, it is easier to integrate this equation in a step by step numerical procedure. In this equation u_o and D_o are initial constants, β (the latitudinal variation of the Coriolis parameter) is considered as a constant, and λ and D are known at every point along a given latitude. Thus this equation is a differential equation in v and x. The boundary conditions are that both v and $\partial v/\partial x$ vanish at a point well to the west of the mountain.

Using finite differences (13) can be written

$$\Delta^2 v/\Delta x^2 = - (D/u_o D_o)\beta v + [(\Delta v/\Delta x + \lambda)/D]\Delta D/\Delta x = 0 \qquad (14)$$

At points along this latitude line to the west of the mountain, no change in v occurs. As soon as a point inside the mountain range is reached, the term $\Delta D/\Delta x$ is no longer zero and a value of $\Delta^2 v/\Delta x^2$ can be obtained. Since the value of $\Delta v/\Delta x = 0$ up to the edge of the mountain, the value of $\Delta v/\Delta x$ can be determined for this first interval. From this value of $\Delta v/\Delta x$ and the fact that $v = 0$ at the edge of the mountain, the north-south component of the velocity at the end of the first interval can be determined. Then the process can be repeated.

At any general point in the computation (14) can be written

$$(\Delta v/\Delta x)_{BC} - (\Delta v/\Delta x)_{AB} = - [D_B \beta \Delta x/u_o D_o]v_B + [(\Delta v/\Delta x)_{BC} + \lambda]\Delta D_{BC}/D_B \qquad (15)$$

where AB and BC are successive intervals, or

$$(\Delta v)_{BC} = M[\Delta v_{AB} + (N + Rv_B)\Delta x] \qquad (16)$$

where:

$$M = D_B/(D_B - \Delta D_{BC}),\ N = (\Delta D_{BC}/D_B)\lambda\ ,\ R = - D_B \beta \Delta x/u_o D_o$$

Beyond the mountain, (14) reduces to

$$\Delta^2 v/\Delta x^2 + (\beta/u_o)v = 0 \qquad (17)$$

Which gives stationary waves of wave length $2\pi\sqrt{u_o/\beta}$ as in the case of Rossby waves.

Typical case--A typical mountain is chosen extending infinitely in a north-south direction. The profile of the mountain is given by a sine squared function of the distance. The base of the mountain is 500 km while the crest is two kilometers high. An initial west wind of ten meters per second is used. The size of the interval Δx was taken as 25 km. The results are shown in Figure 3. The upper curves show the north-south and west-east velocity components as a function of the distance along a given latitude. It must be remembered that in all cases, the values of the velocity components are computed along a latitude line and not along streamlines. The magnitude and direction of the actual velocity vector at any point can be obtained from these values of u and v if desired. The lower curve shows the pressure profile along this latitude. The latitude used is approximately 41°N ($\lambda = 0.941 \times 10^{-4}$ sec^{-1} and $\beta = 1.75 \times 10^{-13}$ sec^{-1}cm^{-1}). The main pressure trough can be seen to be at 1000 km beyond the crest of the mountain.

The above results are in agreement with the discussion by **HOLMBOE, FORSYTHE, and GUSTIN** [1945]. On the windward side the air particles acquire anticyclonic vorticity. Since $\Delta D/\Delta x < 0$, then from (14) the effect of the divergence term $[- (1/D)\Delta D/\Delta x]$ will tend to make $\Delta^2 v/\Delta x^2 < 0$. On the lee side, the particles will gain cyclonic vorticity where the horizontal divergence is negative. As soon as the anticyclonic turning begins, the particles obtain a velocity component toward the south ($v < 0$). Therefore, the latitude term $[- (D/u_o D_o)\beta v]$ tends to counteract the divergence term until the crest is reached. Beyond the crest these two terms are additive. Thus the particles gain more vorticity during the descent than they lost in the ascent. The current will leave the mountain with cyclonic curvature ($\Delta^2 v/\Delta x^2 > 0$). Beyond the mountain range, the particles will gain cyclonic vorticity and curvature as long as v is negative or until the wind becomes a west wind ($v = 0$). The pressure trough will occur at the point where $v = 0$.

A comparison with the results obtained in the graphical method is also shown in Figure 3. While there is qualitative agreement, there is considerable difference in the position and the intensity of the low pressure trough. In the graphical solution with the lateral boundaries, the effect of these boundaries is to deflect the streamlines back to the northerly direction sooner than if there are no such boundaries. Since the λv term is the predominant term in the pressure computations, this will cause the pressure trough to appear closer to the mountain and will have a lower value. The irregularities

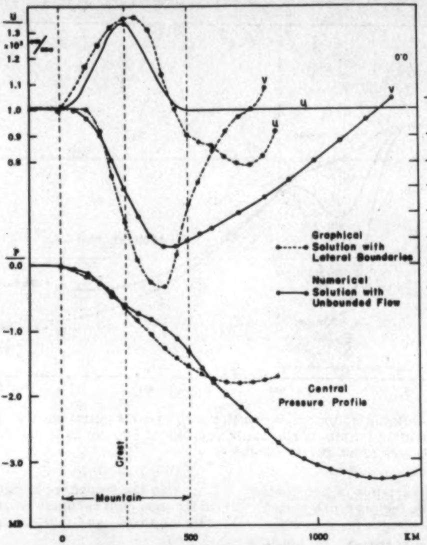

Fig. 3--Horizontal velocity components and pressure profile from an airflow across a north-south mountain of 500-km base and two-kilometer crest with an initial west wind of ten meters per second at 41°N latitude; infinite lateral extent (solid lines), and with fixed lateral boundaries (dashed lines)

in the streamline pattern in the graphical solution are absent in this case.

The procedure in this second part is much quicker than the more laborious and time consuming graphical method. For this reason, it will be advantageous to use the numerical method in studying the relative effects of varying such factors as initial velocity, and shape and size of the mountain profile.

Variation in initial wind speed--As can be seen in Figure 3 there is an indication of a secondary minimum in the pressure profile near the crest of the mountain. If the initial velocity is increased, this secondary trough becomes increasingly important. The results are shown in Figure 4. With $u_0 = 30$ m/sec, the pressure trough at the crest of the mountain is now 3.75 mb. The value of the long wavelength lee trough deepens only slightly from 3.06 to 3.94 mb. The position of this lee trough is 1150 km from the mountain crest in contrast to 1000 km with $u_0 = 10$ m/sec. The reason for the increase in the importance of the secondary trough arises from the fact that the $u\,\partial u/\partial x$ term becomes more important in the computation of the pressure profile.

In a discussion of lee cyclogenesis, HESS and WAGNER [1948] pointed out that preceding the actual cyclogenesis in the Rocky Mountain area, a definite increase in the wind flow perpendicular to the Rockies occurs.

Variation in the height of the mountain crest-- With a 500 km base mountain and an initial west wind of ten meters per second, the lee pressure trough is found to deepen and move in closer to the lee side of the mountain as the height of the crest is increased (see Table 1).

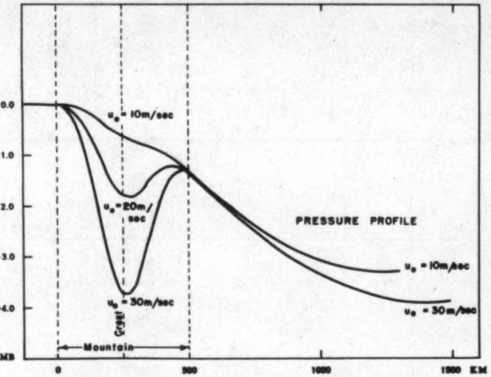

Fig. 4--Resulting pressure profiles with various initial west wind velocities; infinite north-south mountain of 500-km base and two-kilometer crest at latitude 41° N

Table 1--Effect of variation of height of mountain crest on the lee pressure trough

Height of crest	Position of trough beyond mountain crest	Intensity of trough
km	km	mb
2	1000	3.3
3	875	4.2
4	700	4.5

Also the secondary trough near the crest of the mountain becomes increasingly important with the three- and four-kilometer crests.

Variation in width of mountain base--Using a mountain base of 50 km, a crest of two kilometers, and an initial west wind of ten meters per second, a pressure trough appears at the crest of the mountain (see Figure 5). In this example no significant lee pressure trough appears. In the computation of the pressure profile, the effect of the latitude term (λv) is quite small. By varying the initial wind velocity, the intensity of the pressure trough is found to depend on the square of the initial wind velocity. This can be seen in Table 2.

Table 2--Effect of variation of initial wind velocity on the crest trough

u_o	Pressure drop
m/sec	mb
10	0.39
20	1.56
30	3.50
40	6.22

This result is in agreement with the work of FALCONER [1947], who found that the pressure correction term for the pressure on Mt. Washington depends on the square of the observed wind.

Using a 50 km base, a four kilometer crest and an initial wind of 40 m/sec, a pressure drop of 24 mb is found. This is comparable with the value computed by BROOKS [1949] in an article on altimeter corrections who obtained a value of 15.3 mb for a 14,000 ft range and a free wind of 100 mph.

Using a mountain with a 5000 km base, two-kilometer crest with an initial west wind of ten meters per second, the results are shown in Figure 6. Deep pressure troughs and ridges are set up in this case. The wavelength of the lee waves beyond the mountain is 4800 km which is in agreement with the wavelength of the Rossby stationary waves for this initial wind velocity. In this particular mountain profile, increasing the initial wind speed has little effect on the resulting pressure profiles. In this example, no pressure trough appears at the crest of the mountain. This is true

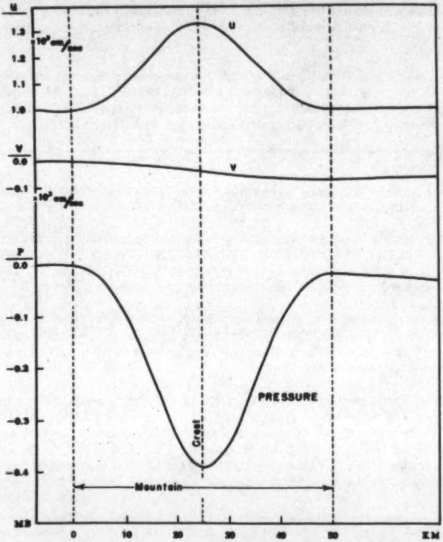

Fig. 5--Horizontal velocity components and pressure profile across an infinite north-south mountain of 50-km base and two-kilometer crest, initial west wind of ten meters per second, latitude 41°N

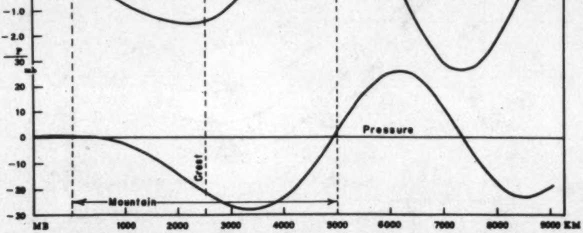

Fig. 6--Horizontal velocity components and pressure profile across an infinite north-south mountain of 5000-km base and two-kilometer crest, an initial west wind of ten meters per second, latitude 41°N even with larger initial wind velocities. With a given mountain crest, the effect of the $u\,\partial u/\partial x$ term in the computation of the pressure profile becomes the predominant term only in the smaller base mountains.

Variation in initial wind direction-- The question arises as to what changes will occur if the initial flow is from some other direction than due west. In this case, the value of $(\Delta v/\Delta x)_o$ is taken as 0 at the windward edge of the mountain, but the value of $v_o \neq 0$. To the left of the mountain, the value of v does not remain constant but varies in accord with the relation

$$\Delta^2 v/\Delta x^2 + (\beta/u_o)v = 0$$

In other words, there will be standing waves whose wavelength is given by $2\pi\sqrt{u_o/\beta}$. The western edge of the mountain is thus placed at a point of inflection relative to these standing waves.

Using a mountain with a 500-km base and two-kilometer crest the initial west-east component of the velocity is fixed at five meters per second and the north-south components are chosen in such a way to make the initial wind direction successively 30°S of W, 15°S of W, 15°N of W, and 30°N of W. The resulting pressure profiles in the x direction are shown in Figure 7.

The deepest pressure trough occurs with the 30°N of W initial flow and the weakest trough occurs with the 30°S of W initial flow. The latter trough occurs at the farthest distance from the mountain crest. As the initial wind becomes more southerly, a pressure ridge becomes more prominent to the windward of the mountain crest.

The explanation of the above results lies in the fact if there were no mountain, the stationary waves (of wavelength about 3370 km) would continue. In the case of the initial wind 30°S of W, there would be a pressure ridge of 1.4 mb at about 840 km. In the case of the initial wind 30°N of W there would be a pressure trough of 1.4 mb at this distance. Thus the effect of the mountain is to change the normal pressure ridge into a weak trough in the case of the winds with the southerly components and to intensify the trough in the case of the initial winds with the northerly components.

In another example, u_o is taken as ten meters per second and v_o as 2.679 m/sec (that is, an initial direction of 15°S of W). If the western edge of the mountain is placed at a point of inflection relative to the existing standing waves west of the mountain (that is, no initial vorticity or $(\Delta v/\Delta x)_o = 0$), a trough of 2.52 mb occurs 1100 km beyond the mountain crest. Placing the western edge of the mountain not at an inflection point but at a point relative to an existing standing wave such that u_o and v_o are the same as before but where $(\Delta v/\Delta x)_o = +0.03544 \times 10^{-4}$ cgs units (that is, initial posi-

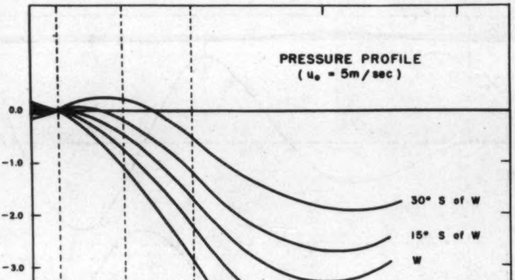

Fig. 7--Pressure profiles for various directions of the initial air flow across an infinite north-south mountain of 500-km base and two-kilometer crest, latitude 41°N tive vorticity), a trough of only 0.8 mb occurs 700 km beyond the mountain crest. Choosing a case such that u_o and v_o are the same but $(\Delta v/\Delta x)_o = -0.03544 \times 10^{-4}$ cgs units (that is, initial negative vorticity), a trough of 5.25 mb occurs 1500 km beyond the mountain crest.

Thus it can be seen that if the initial direction of flow is not westerly, the position and intensity of the lee pressure trough depends on the relative position of the western edge of the mountain and the standing waves existing west of the mountains (that is, upon the values of u_o, v_o, and $(\Delta v/\Delta x)_o$).

Comparison with theoretical work of QUENEY [1947, 1948]--The mountain profile with a two kilometer crest and a 500-km base is comparable with Queney's typical broad mountain range. His results show a secondary pressure trough just beyond the crest of the mountain and lee waves in the ground level streamline pattern of wavelength approximately 600 km. However, no lee patterns are present in the ground level pressure profile. The fact that he neglects the β term in this particular example prevents the occurrence of a lee pressure trough further downstream as is found in Figure 3 in this paper. Also his results show a pressure ridge to the windward side of the mountain crest which does not appear in Figure 3.

The 50-km base mountain with crest height of two kilometers discussed under Variation in width of mountain base, is comparable to Queney's medium size typical mountain range. His results show a ground-level pressure trough of 0.6 mb just beyond the crest of the mountain as compared with the 0.4 mb trough as shown in Figure 5. Again the ridge of 0.6 mb in Queney's results to the windward side of the mountain crest does not appear in Figure 5 in this paper.

The 5000-km base mountain with crest height of two kilometers is comparable to Queney's very broad typical mountain range. The results are in good agreement except for the pressure ridge which appears in his results to the windward side of the mountain crest.

In all cases, using an initial west wind flow, no pressure ridge appears in the results in this paper. However, if standing waves are assumed to exist to the windward of the mountain, so as to give an initial southwest wind at the edge of the mountain, it is possible to show an initial pressure ridge.

Using an idealized Rocky Mountain profile--In order to investigate more carefully the location and intensity of the long wavelength pressure trough, it is desirable to use a profile more nearly approximating the Rocky Mountains in western United States. Referring to some cross sections given by CROWLEY [1944], the following smoothed profile at 39°N is set up: Start from zero at 122°W, rise to a peak of 2.5 km at 117°W, descend to 1.5 km at 111°W, rise to a peak of 3.0 km at 106°W, and descend steeply to 103°W and more gradually to 93°W. It must be assumed that this profile extends indefinitely in the north-south direction $(\Delta G/\Delta y) = 0$. With an initial west wind of ten meters per second resulting pressure profile is shown in Figure 8. A trough of 22.6 mb occurs at 94°W. If the initial west wind is reduced to five meters per second the intensity of the trough is 14.66 mb at 97°W. If the initial velocity is increased to 20 m/sec a trough of 31.6 mb occurs at 89°W.

Using an idealized profile at 47°N and initial west wind of ten meters per second a pressure trough of 18.5 mb occurs at 93°W. Using an idealized profile at 35°W, a 14.80-mb trough appears at 94°W. Thus the location of the pressure trough occurs at nearly the same longitude in all three cases, but the deepest pressure trough occurs along the 39°N latitude. The mountain crest has the highest value along this latitude. While the values of the lee pressure trough intensities seem high, it must be remembered that such effects as friction and convergence due to other effects beyond the mountain are neglected. The important results are to be found in the relative values and positions of these pressure troughs under different conditions rather than any particular absolute value.

In a paper by BYERS and STARR [1943], normal maps are given for January. The two-kilometer chart shows a pressure trough between 35°N 100°W and 70°N 80°W; the four-kilometer chart shows a trough between 35°N 100°W and 65°N 90°W. More recent upper level charts can be found in the Joint Meteorological Committee publication "Normal Weather Maps, Northern Hemisphere, Upper Level" issued in 1944. An examination of the normal 10,000- and 20,000-ft, 10-, 13-, 16-, and 19-km charts for the winter months November, December, January, and February show pressure troughs in most cases between 80° and 90°W. No attempt is made to isolate the cases in which the average wind along the west coast is more nearly normal to the mountain range. Possibly a better check could be found from a frequency distribution of the location of the upper level troughs. Such a study is underway at the Extended Forecast Section of the United States Weather Bureau.

An examination of a series of five-day mean upper level maps (700 mb or 10,000 ft) shows several examples of the formation of a trough in the area of 90°W when the preceding chart (or charts) showed a good westerly flow along the west coast. A typical example is shown in Figure 9.

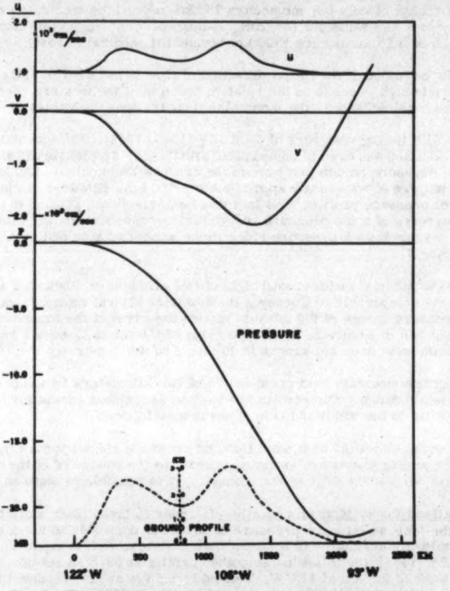

Fig. 8--Horizontal velocity components and pressure profile across an infinite north-south mountain profile patterned after an idealized profile through the Rocky Mountains at 39°N; initial west wind of ten meters per second

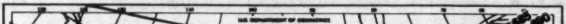
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Fig. 9--10,000-ft isobars on successive five-day mean maps

In this instance, the trough which developed near 90°W on the November 10-14, 1937 mean map remained in this general vicinity through the November 27 - December 1, 1937 map.

An unpublished study of the location of sea-level, low-pressure centers over the United States was made for the years 1934-1937 and 1941-1943 by the Short Range Forecast Development Section of the United States Weather Bureau. This study shows a concentration of lows along a band between 90-95°W longitude using the entire data. Using the six months totals (October through March) a similar concentration is shown along the same band for middle latitudes and the band between 85-90°W for the higher latitudes (see Figure 10). The eastward displacement in the higher latitudes might be expected because of higher mean wind velocities along these latitudes. An examination of the data for April through September shows a concentration along the bands from 95-105°W. This displacement of the concentration between the winter and summer seasons is in reasonable agreement with the theoretical results. The trough shifted from 89°W for an initial west wind of 20 m/sec to 97°W for an initial west wind of five meters per second. Using the three month period (December - February) a pattern similar to that for October - March is found with an eastward displacement of the concentration along the northern latitudes. Also a secondary maximum is found between 100-105°W and 35-40°N. This is in accord with the increasing importance of the secondary trough along the mountain crest with the increasing wind velocities as noticed in the section on Variation in initial wind speed.

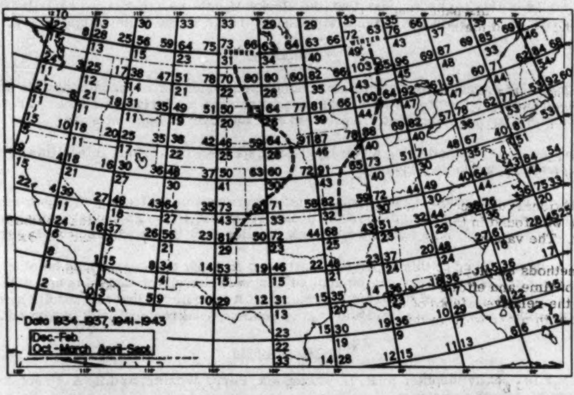

Fig. 10--Geographical distribution of surface low-pressure centers; upper left hand corner, total number of cases for December through February; lower left hand corner, October through March; lower right hand corner; April through September; obtained from unpublished study of Short Range Forecast Development Section, United States Weather Bureau

While the above observational data cannot be taken as positive proof of the throretical work in this paper, it is felt that the results of this study are in good qualitative agreement with the observed data.

The existence of a trough over the continental United States has been recognized and discussed by others and it was the basis of considerable work by ROSSBY [1939, 1940]. He pointed out that an examination of five-day mean isentropic charts and pressure charts for the three-kilometer level shows a trough over the United States during the winter season. He discussed the effect of the solenoidal field concentration as one source of the perturbation of the zonal westerly flow. During the summer season there is a maximum concentration of the solenoidal field on the West Coast and in the winter season along the East Coast. According to Rossby each of these zones will set up nearly stationary perturbations in the zonal flow and in the trail of this perturbation a series of stationary waves will develop. The wavelength of these standing waves should be 6000 km in the winter (zonal current of 16 m/sec) and 3000 km in the summer (zonal current of four miles per second). Rossby points out that the solenoidal field on the west Coast in conjunction with the steep mountain ranges will set up a trough near the coast and a series of standing perturbations in the pressure distribution further downstream.

The question arises as to how much of the cause of this low presssure trough over central and eastern United States can be attributed to the effects of the Rocky Mountains. In the winter season the intense solenoidal field is along the east coast and quite weak along the west coast. Yet an examination of the upper level charts show the most pronounced troughs over central and eastern United States during this season. The distance of the troughs from the West Coast found in this paper and from the above observational data is between 2000 to 2500 km. These distances are considerably smaller than would be expected using the solenoidal field as the sole cause of the standing waves. Certainly the results of this paper suggest that the Rocky Mountains are a large contributing factor in the production and maintenance of the low pressure trough in the Mississippi Valley.

Summary

Throughout this paper, the equations were developed assuming an incompressible and homogeneous atmosphere. However, the same basic equations can be derived for other barotropic atmospheres such as one having an adiabatic lapse rate and adiabatic changes of state.

A further study is planned using a two layer atmosphere with varying intensities of the temperature inversions between the two layers.

An additional justification of the assumptions concerning the neglecting of such terms as $\partial u/\partial y$ and $\partial v/\partial y$ was found in the calculation of the pressure profile in the graphical method in Part 1 of this paper. The values of these terms were much smaller than the $\partial u/\partial x$ and $\partial v/\partial x$ terms.

The methods employed in this paper are quite easy to apply and results can be obtained with a minimum of time and effort. They can be applied to a wide variety of examples and will give a good picture of the relative effects of different parameters. It is believed that the results are in good agreement with other work in this field and in good qualitative agreement with observational data.

Acknowledgments

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Washington, D. C.

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INTERPRETATION OF BIKINI MAGNETIC DATA

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Abstract--A magnetic model study of Bikini indicates that basement material rises to within 5000 ft of sea level approximately one mile to the northeast of Bikini Island. The model assumes uniform susceptibility and zero permanent magnetization and conforms to known seismic profiles of the basement.

Introduction--During the summer of 1947 a large scale airborne magnetic survey was made in Alaska and in the Marshall Islands sponsored jointly by the Office of Naval Research, the U. S. Geological Survey, and the Naval Ordnance Laboratory. A part of this project resulted in the detailed magnetic field total intensity contour map of Bikini Atoll shown in Figure 1 [ALLDREDGE and KELLER, 1949]. We have interpreted these magnetic data in terms of a possible basement structure by the use of model techniques.

As is well known, there are an infinite number of different configurations of magnetic materials which could account for the observed data given in Figure 1. In spite of this ambiguity, we felt that some useful ideas might arise from determining a possible magnetic substructure, based

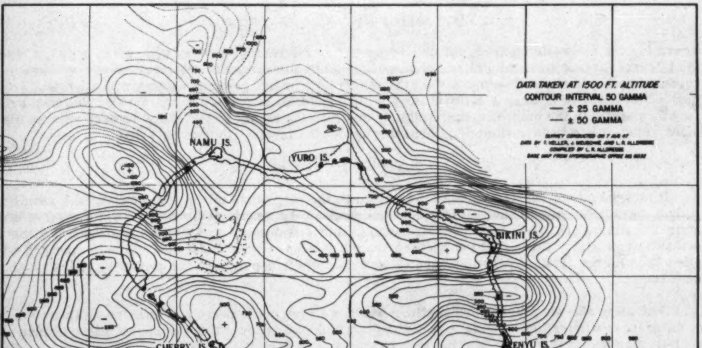

Fig. 1--Total magnetic intensity anomaly contour map of Bikini Atoll upon a few elementary assumptions.

It is realized that randomly oriented permanent magnetization and variations in susceptibility account for large anomalies in many places throughout the Earth and there is no assurance that these factors are not important in the case of Pacific atolls. A model which admits these variables and which matches the observed magnetic data could be built. In fact any number of such models could be built. Complicated models of this type would yield substructures which would be very difficult to interpret. To simplify the problem it was decided to assume zero permanent magnetization and uniform susceptibility. Such a simple model must have topographic relief to account for the observed data. The propriety of these simple assumptions can be judged only after the predictions of such a model are checked by other geophysical methods.

Description of model techniques--We assumed that a smooth basement surface where Bikini now stands would result in a uniform magnetic field of 345 milligauss with a dip angle of + 13.5° and a declination of 5°E. This is the present average field. This uniform field was applied to the model using a 20-ft three-dimensional coil system with the model placed in the center. Bikini is very near the geomagnetic equator having a geomagnetic latitude of approximately 6.5°. The north-south total field gradient is less than three gamma per mile and was therefore neglected.

A mixture of foundry clay, ground magnetite, linseed oil, and glycerine was used for the model material. For the base of the model very little glycerine was used. As the oil dried out an unyielding base was formed to support the upper part of the model. Glycerine was mixed with that clay used on the top part of the model so it would remain soft for later reshaping. Before construction of the model, the clay mixture was thoroughly demagnetized by applying an alternating field of diminishing amplitude in zero background field.

The magnetic potential V(x, y, z) at points outside the magnetic material is given by

$$V(x, y, z) = \int [\vec{I}(x', y', z') \cdot \vec{r}/r^3] dv \qquad (1)$$

where $\vec{I}$ is the magnetic moment per unit volume, $\vec{r}$ is the vector between x, y, z and x', y', z' and the integral extends over the entire volume occupied by the magnetic material. Since we have assumed zero permanent magnetization, the magnetic moment per unit volume will all result from induced magnetization when a uniform magnetizing field Ho is applied to the model. We may write $\vec{I} = k\vec{H}$, where k is the magnetic susceptibility and H is the actual field applied to each volume element. Since k has been assumed uniform throughout the model, (1) may be written

$$V = k \int (\vec{H} \cdot \vec{r}/r^3) dv \qquad (2)$$

It is now evident that the value of k can change the magnitude of the potential and the resulting potential gradient but can have no effect on the shape of the resulting field (that is, location of maximum and minimum). The shape of the resulting field will depend on $\vec{H}$ and the boundaries of the magnetic material. These last two factors are not independent as $\vec{H}$ depends not only upon the applied field $\vec{H}$o but also upon the demagnetizing factor which depends on the geometry of the magnetic material.

With all of the simplifying assumptions which we have made there may still be an infinite number of different configurations of magnetic material which can account for the known shape of magnetic contour map shown in Figure 1. This lack of uniqueness is best seen by assuming we have a potential which fits a single dipole. Since any ellipsoid of revolution is equivalent to a centered dipole as far as induced magnetic effects are concerned, any number of such configurations could be made to produce the required potential. If, however, nine points were known on the boundary, the proper ellipsoid of revolution would be uniquely determined.

Fortunately, in the case under consideration something is known about the boundary conditions. Recent work by DOBRIN, PERKINS and SNAVELY [1949] gives four seismic profiles across the lagoon at Bikini. Their conclusion based upon refraction shooting is that the velocity zone of 17,000-ft/sec marks basement material. Their data show that along the four profile lines the elevation of the upper boundary of this zone varies from 7000 ft to 13,000 ft below sea level. This boundary information limits, to some extent, the ambiguity inherent in (2) and permits a better determination of the substructure within the original simplifying assumptions of zero permanent magnetization and uniform susceptibility.

The choice of k is not critical as has been shown. The general shape of the substructure can be determined using any value of k which can then be adjusted to obtain the correct magnitude.

To determine a likely value of k it was noted that the susceptibilities of various magnetic minerals and rocks are given by CHAPMAN and BARTELS [1940] as: Basalt (Northumberland), k = 0.0002 to 0.01; mean of 45 dolorites and basalts from the British Isles, k = 0.0026; lava from Mount Etna, k = 0.008.

In addition a simple calculation was made assuming that the general features of Figure 1 were caused by a uniformly magnetized sphere. The data on Figure 1 do not go to seaward far enough to establish definitely the location of the fringe peaks. It is estimated, however, that they occur approximately 30 mi apart for a north-south profile line over the center of the lagoon. Using this value for the separation in the peaks, assuming that the basement material rises to within 7000 ft of sea level on the basis of the seismic work, substituting 34,000 gamma as the applied field, and putting in -700 gamma as the magnitude of the central negative peak (see Figure 1), a value of 0.008 for k was obtained. This value was used throughout the model work. No readjustment of k was required after the general shape of the substructure was determined. This value of k was obtained by adding the proper amount of magnetite to the clay.

The model technique as described above avoids the erroneous assumption of uniform magnetization which is common to many methods where magnetic fields are synthesized mathematically by adding uniformily magnetized sections of material.

The resulting magnetic anomaly caused by the model was recorded using a miniature magnetometer carried at the proper height above the model by an automatic traverse system. This procedure yields a magnetic contour map which can be compared with the original magnetic data.

The miniature magnetometer used in the model work was capable of measuring only a single magnetic component, whereas the original data were taken using an orienting total field detector. The anomalous field of Bikini has a small value when compared to the Earth's field. In this case only the component of the anomaly in the direction of the Earth's field produces an appreciable effect on a total field magnetometer. For this reason a single component magnetometer may be used in the model work as long as its detection axis is maintained in the direction of the Earth's field as was done in this work.

The miniature magnetometer has a sensitive core element approximately 5/8 of an inch long. For the scale used, this represents approximately 2500 ft. The field indicated by the magnetometer is roughly the average field in this 2500-ft distance. This tends to decrease both negative and positive peak values. This averaging process is not serious in this case as can be judged from Figure 1. The miniature magnetometer system is accurate to only ±50 gamma.

SINCLAIR [1948] has given a rather complete discussion of the relationship required between a full scale system and a model system. In this model work we have scaled all linear dimensions and have adjusted the susceptibility of the model to be equal to that of the full scale object. Under these conditions, equal fields applied to the object and model produce the same magnetic states, and the resulting model field when measured at the scaled distance, is equal to that of the object.

Construction of model--The size of the model was limited by the dimensions of the large coil system used to apply the field found at Bikini, and by the limitations of the automatic traverse system used to carry the magnetometer over the model. Two nautical miles on the Atoll were made equivalent to three inches on the model. The model scale factor was therefore approximately 1/48640.

The general ocean depth in the area surrounding Bikini is 2500 fathoms. In our first model, we let the plywood board upon which the model was to be constructed represent this depth below sea level. Copper nails were driven into the plywood board so that their heads indicated the proper depth below sea level of the upper surface of the basement material as indicated by the seismic data. Magnetic clay was then placed on the board and molded flush with the heads of the copper nails. In regions void of seismic data, the clay was formed roughly into peaks where Figure 1 indicates magnetic lows and into low places where magnetic highs are indicated.

A survey with the magnetometer showed where the model data differed from the full scale data. Suggested changes were made, always keeping the seismic profiles invariant in an attempt to obtain a model which would reproduce the full scale data.

We soon found that with our first model the seismic and magnetic data were incompatible if the uniform susceptibility assumption was to be retained. There was no way to account for the general decrease in magnetic field in moving from Yuro toward Enyu Island without violating the seismic data in this same region. Not desiring to abandon the uniform susceptibility assumption, since to do so would make any contour predictions about the basement in regions not covered by the seismic data impossible, we searched for another solution.

The above incompatibility of data was removed by adding an equivalent 7000-ft thick slab of the magnetic clay to the underside of the model. By cutting a rather steep side on the eastern end of the south side of the mound and gradually sloping the clay on all the other edges, we were able to match the magnetic data without violating the seismic profile lines.

This new model is equivalent to assuming that the general basement underlying the ocean floor begins a little more than a mile beneath the present ocean floor.

Results--Figure 2 shows the magnetic contours resulting from the final model. A basement relief (topographic) map of the final model is shown in Figure 3. In most places the magnetic contou lines of the model agree quite well with the original magnetic anomaly map (Fig. 1). The fact that this model shows a string of topographic highs around the atoll fringes with major peaks near each island adds strength to the simple assumption of uniform susceptibility. The only place where this is not true is near Cherry Island where a topographic low is shown.

The model predicts that the basement rises to its highest peak approximately one mile to the northeast of Bikini Island. At this point the basement is only 5000 ft below sea level. The water over this peak is 3000 ft deep leaving only 2000 ft of nonmagnetic material. The model predicts 8000 ft to the basement at the northeast edge of Bikini Island.

On high peaks such as occur northeast of Bikini Island and to the north of Enyu Island, changes in model height of 1/4 inch (1000 ft) could easily be detected magnetically. In the center of the large flat area between Yuro and Enyu Island changes in height of 3/8 inch (1500 ft) were barely detectable magnetically. As would be expected the depth resolution was even less precise in craters such as the one to the northeast of Cherry Island.

The general location of the seismic profile lines are indicated by dashed lines in Figure 3. The seismic control did not, however, extend along the entire length of the dashed lines. The magnetic fit as shown was obtained by following the seismic data carefully except in the region of Cherr Island. Over a small area in this region model depths were 2000 ft deeper than those shown by the seismic data. This deviation from the seismic data permitted a better magnetic fit. DOBRIN,

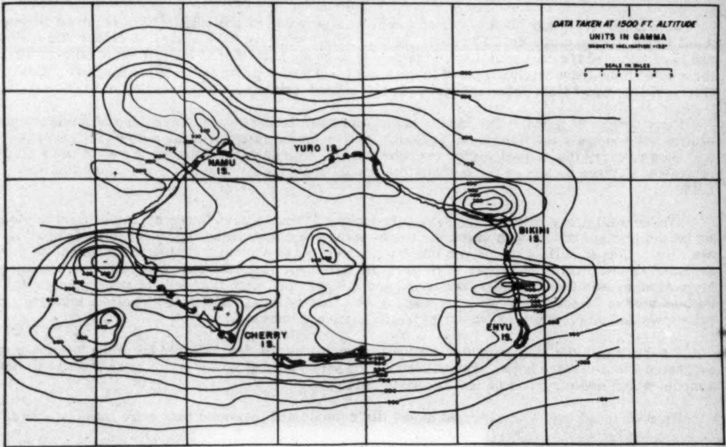

Fig. 2--Total magnetic intensity contour map of model of Bikini Atoll

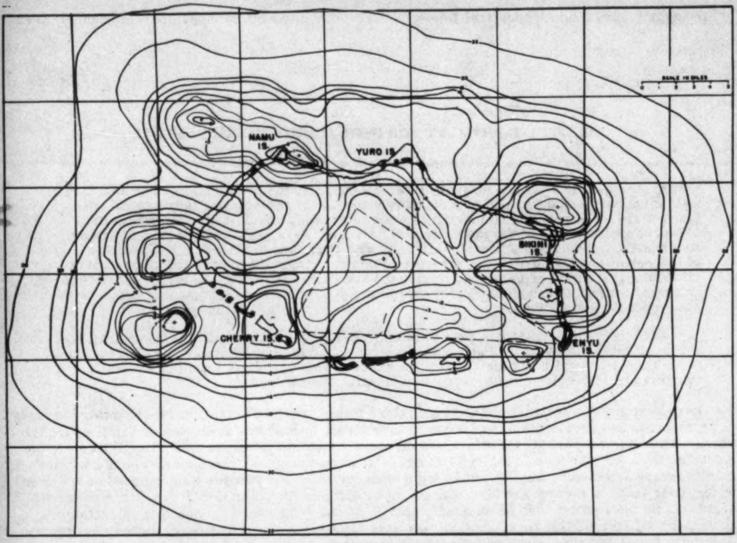

Fig. 3--Basement relief map of model of Bikini Atoll, contours in thousands of feet below sea level (low numbers indicate mountain peaks)

PERKINS and SNAVELY [1949] point out that their conclusions might be in error by as much as 1500 ft on the basement. The large crater northeast of Cherry Island was necessary to match the magnetic data. The depth of the crater was found to make little difference so long is it was made greater than 14,000 ft deep. The exceedingly steep sides were necessary to match the magnetic data to the north of the crater.

Since the clay was tapered off to zero thickness on all sides of the model, neither the magnetic or topographic maps would be expected to be accurate near the northeast corner of the Atoll where a seamount is known to connect with the Atoll.

The magnetic contour map of the seamount adjacent to Bikini Atoll showed a greater magnetic low than Bikini. If these same model techniques were extended into this region it is quite sure that the basement would rise to the full height of the seamount (4000 ft below sea level).

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AIRBORNE EQUIPMENT FOR GEOMAGNETIC MEASUREMENTS

L. H. Rumbaugh and L. R. Alldredge

Abstract--The airborne magnetometer AN/ASQ-3A has been modified and auxiliary equipment has been developed to meet requirements for constructing isomagnetic contours of the total magnetic field over extensive areas for use in magnetic prospecting. The principal features of the instrument system are: (a) a self-oriented magnetometer which utilizes the output of a system of saturable inductors to provide a d-c response of low noise level and drift rate; (b) instruments for aiding the pilot to follow predetermined lines of a grid or network covering the area to be explored; and (c) an interlocked group of recorders for automatically correlating a continuous magnetometer record with plane position and altitude.

The system described has been used extensively by the United States Geological Survey, the United States Naval Petroleum Reserves, and the United States Naval Ordnance Laboratory in aerial magnetic exploration under a wide variety of conditions. Similar systems are also being used by a few commercial companies.

Introduction--The Naval Ordnance Laboratory (NOL), as the principal naval laboratory for magnetic research and development, has engaged extensively in magnetic problems during the past eight years. An important part of this effort was directed toward the development and application of the saturable inductor principle in a large number of sensitive magnetic instruments, including various mobile magnetometers capable of producing continuous magnetic records when carried or towed in water, over land, or through the air. The magnetic airborne detector (MAD) has attracted considerable public interest because of its adaptability to aerial geophysical prospecting. Contractors associated with the NOL in these applications were General Electric Company, Pioneer Instrument Company, Leeds and Northrup Company, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and the Bell Telephone Laboratories.

Many reports on various aspects of the airborne magnetometer detector have appeared in various journals during the past two or three years, but a complete story has not been published in a single article which is readily available to geophysicists. For this reason, it was thought appropriate to prepare this article as a review article touching not only upon the details of the magnetometer construction but also covering other phases of the problem that are necessary for successful aerial magnetic mapping.

Methods of detecting small magnetic fields--There are three common methods for detecting a component of magnetic field or variations in its magnitude: (1) by the mechanical force produced by a magnetic field acting on a magnet or an electric current; (2) by the emf induced by relative motion between a magnetic field and an electrical conductor; (3) by use of a functional relationship between a magnetic field and some physical property, for example, permeability and resistivity of a material. It may be noted that all but the third of these methods imply the concurrent use of mechanical devices for detecting a static magnetic field.

Geophysical applications often require the detection or measurement of magnetic field variations smaller than 10^{-4} times the Earth's field at the detector as it is moved through space; that is, the combined mechanical, electrical, and magnetic stability of the detecting system must be sufficient to reduce the over-all noise to about one gamma (one gamma = 10^{-5} oersted) against a background of about 0.5 oersted from Earth's ambient field. Until recently, this severe requirement had been met in a limited manner by only the first of the above three methods for detecting magnetic fields. Magnetic anomalies commonly were mapped by a succession of discrete measurements at stations on the ground by the use of highly sensitive, mechanically-balanced magnetometers requiring careful leveling on rigid bases [JOYCE, 1937].

The saturable inductor, sometimes called "fluxgate" or saturated core reactor, is an example of the third of the above methods for detecting magnetic fields. The saturable inductor makes use of the variation of permeability with intensity of magnetization in a ferromagnetic core. The principle has been accepted for a long time, but apparently was put to practical use in the measurement of magnetic fields only recently [ELMEN, 1936; ANTRANIKIAN, 1936]. Perhaps the earliest use of the saturable inductor to measure small magnetic disturbances was by ASCHENBRENNER and GOUBAU [1936].

The important feature of the saturable inductor is that it permits a magnetic field to be detected and measured by purely electrical means without the use of any mechanically moving parts within the detector. This feature permits the saturable inductor simultaneously to satisfy requirements for high sensitivity, continuous recording, and instrumental stability in a mobile magnetometer. Sensitive magnetometers employing this principle can be successfully used in aircraft where shock and vibration prohibit the use of sensitive magnetometers of other types. In many cases airborne magnetic measurements can replace costly surface surveys at a greatly reduced cost [JENSEN, 1946].

The saturable inductor--If an easily saturable ferromagnetic core of high permeability (supermalloy, mu-metal, or permalloy) is driven cyclially into saturation by an applied magnetomotive force in the presence of a component of external magnetic field, H_o, parallel to the axis of the core (see Fig. 1), the output emf e will have an asymmetrical wave form (see Fig. 2) containing both even and odd harmonics of the driving frequency.

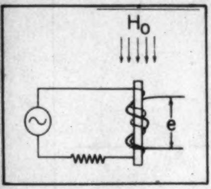

Fig. 1--Elements of the saturable inductor

When the external field is decreased, the even harmonics, which cause asymmetry, are suppressed, but the driving frequency and its odd harmonics remain.

By neglecting hysteresis for the moment, the even and odd harmonic content of e may be demonstrated analytically in a simple manner. It is evident from the symmetry of an idealized B-H curve that the flux density B may be expressed as an odd power series in H

$$B = \sum_{n=0}^{\infty} b_{2n+1} H^{2n+1}$$

where coefficients b are fixed by the geometry and material of the core and H is the sum of the external field and the driving field

$$H = H_o + h_o \cos \omega t$$

By examination of the general term $(H_o + h_o \cos \omega t)^{2n+1}$ it is seen that the binomial expansion will give even powers of $h_o \cos \omega t$ multiplied by odd powers of H_o in addition to odd powers of $h_o \cos \omega t$ multiplied by even powers of H_o.

All even (odd) powers of the cosine may be expressed as the sum of the cosines of even (odd) multiples of ωt. The corresponding coefficients are even (odd) functions of H_o and odd (even) functions of H_o

$$B = \sum_{n=0}^{\infty} B_n(H_o, h_o) \cos n\omega t$$

where the coefficients B_{2n} of the even harmonics are even functions of h_o but odd functions of H_o, while the coefficients B_{2n+1} of the odd harmonics are odd functions of h_o and even functions of H_o.

The output emf is given by $e = -10^{-8} NA (dB/dt)$, where NA means the effective area turns in the output coil. It follows immediately that e is $(-10^{-8} NA)$ times the sum of even harmonic terms $2n\omega B_{2n} \sin 2n\omega t$, and odd harmonic terms $(2n+1)\omega B_{2n+1} \sin (2n+1)\omega t$. The even harmonic terms vanish for H_o equal to zero, while the odd harmonics do not vanish. Likewise, only the even harmonics are sensitive to the sign of H_o.

Saturable inductor detection circuits--In principle, any coefficient or combination of coefficients B_n in the equation for the cyclically-driven saturable inductor may be used for detection since all B_n are functions of the external field H_o. However, the even harmonics indicate the polarity of the external field and vanish for zero external field, while the odd harmonics do neither. Furthermore, the fundamental driving frequency coefficient, B_1, contains a particularly large and useless "background" term μh_o. Consequently, it is general practice to segregate the odd harmonics together with the fundamental and employ only even harmonics for detection.

Two general types of even harmonic detection have been employed. Each type has its peculiar advantages and disadvantages. The choice of one or the other depends upon the requirements which are emphasized in the application.

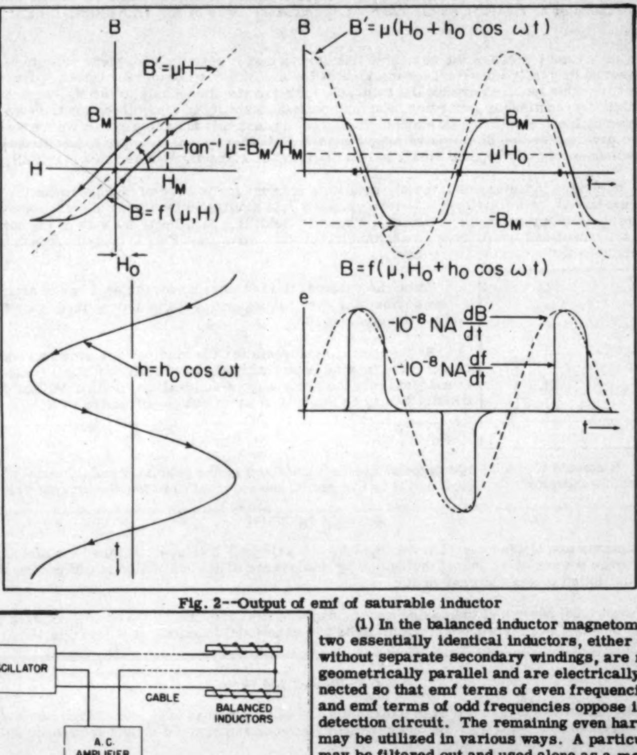
B
$B' = \mu H$
B_M
$\tan^{-1} \mu = B_M/H_M$
H
H_M
$B = f(\mu, H)$
H_0
$h = h_0 \cos \omega t$
B
$B' = \mu(H_0 + h_0 \cos \omega t)$
B_M
μH_0
t
$-B_M$
$B = f(\mu, H_0 + h_0 \cos \omega t)$
e
$-10^{-8} NA \frac{dB'}{dt}$
$-10^{-8} NA \frac{df}{dt}$
t

Fig. 2--Output of emf of saturable inductor

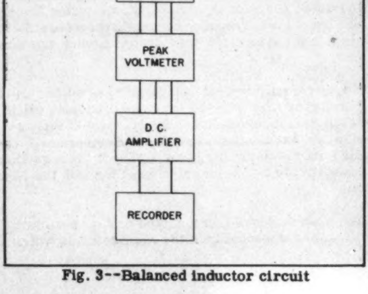
OSCILLATOR
CABLE
BALANCED INDUCTORS
A.C. AMPLIFIER
PEAK VOLTMETER
D.C. AMPLIFIER
RECORDER

Fig. 3--Balanced inductor circuit

(1) In the balanced inductor magnetometer, two essentially identical inductors, either with or without separate secondary windings, are made geometrically parallel and are electrically connected so that emf terms of even frequencies add and emf terms of odd frequencies oppose in the detection circuit. The remaining even harmonics may be utilized in various ways. A particular one may be filtered out and used alone as a measure of the field or the resultant wave form may be used with a peak amplitude indicator. One variation of this type of detector using all even harmonics is shown in Figure 3. With carefully balanced inductor and amplifiers, the circuit shown will operate in a fixed position with a signal-noise ratio of ten at a sensitivity of one gamma. Its earliest use was in single component magnetometers and highly sensitive gradiometers, particularly those developed by the Naval Ordnance Laboratory and its associated contractors listed above. The MAD system AN/ASQ-1, developed by the National Defense Research Council during the war, and the Gulf Research and Development Company airborne magnetometer [MUFFLY, 1946] also incorporate features of this circuit. Such a system starts with a larger signal than systems which select single harmonics, but requires wide-band amplification.

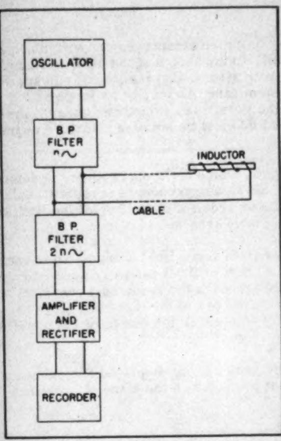

Fig. 4--Second harmonic inductor

(2) In a magnetometer where only a single harmonic is to be used, a simpler system with a single inductor [FELCH and Others, 1947] shown in Figure 4, can be employed. The inductor is excited through a band-pass filter designed to eliminate all but the fundamental frequency of the driving oscillator. One of the even harmonics generated in the inductor is selected and fed to the amplifier and recorder through a second band-pass filter. This filter must be sufficiently narrow to reject the two odd harmonics closest in frequency to the even harmonic selected for detection. With carefully designed filters and regulation of the driving oscillator, this circuit, like the first, can be designed to detect magnetic fields of less than a gamma. This type of circuit is particularly useful in applications requiring a simple inductor in a small space. The second harmonic single inductor-detector arrangement shown in Figure 4 is basic in the MAD system AN/ASQ-3A used by the Naval Ordnance Laboratory and the United States Geological Survey for geophysical exploration.

The proper degree of excitation to use in a single frequency harmonic detector can be approximately calculated if a simplified magnetization curve is assumed. By reference to Figure 2, it may be seen that hysteresis introduces an inconsequential and constant phase shift in B and in e. Suppose the inductor core characteristics are approximated by three straight line segments, $B = \mu H$ for $|B| \leqq B_M$, and $B = \pm B_M$ for $|B| \geqq B_M$, where μ is the effective permeability, determined principally by core geometry, and B_M is the flux density at saturation. This idealization will produce two effects in the plots of B and e against time t: (1) the time lag between the solid and the dotted curves will be removed and the two will be in phase; (2) because of the sharp inset of saturation, the transitions between the sinusoidal and the straight line portions of the curves will be abrupt and the resulting curves will be composed only of portions of sinusoidal curves and straight line segments of zero and of infinite slopes. The idealized curve for emf as a function of time can be analyzed into Fourier components. The Fourier coefficients of each harmonic frequency in the output emf can be computed and further used for calculating the sensitivity, $(\Delta e)/(\Delta H_o)$, of an idealized inductor. Figure 5 shows the results of such a calculation applied to the second harmonic of the output emf. The agreement in Figure 5 between the computed sensitivity of an ideal inductor and the measured sensitivity of an actual inductor shows that the core material used (4-79 permalloy) closely approaches the magnetic characteristics of an ideal core material for measuring small external fields (H_o small compared to H_M) and indicates that the amplitude of the driving field for maximum sensitivity is roughly one and one-half times the saturation field for the core material.

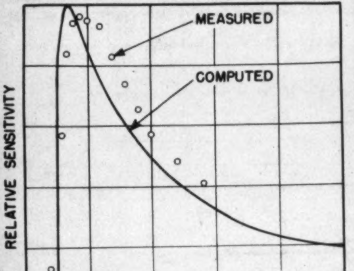

Fig. 5--Variation of sensitivity with the amplitude of the driving field h_o

Orientation and mechanical stability of inductor systems--The magnetic field measured by a single inductor will be $H_e \cos\phi + H_o \cos\theta$, where $H_e \cos\phi$ is the part attributed to the Earth's total magnetic field when the angle between it and the inductor axis is ϕ, and $H_o \cos\theta$ is the part attributed to an anomalous field vector at an angle θ with the inductor axis.

If the inductor is moved to a new position, the change in field which it will indicate will be approximately

$$\Delta H = H_e \left\{\cos\phi\,(\cos\Delta\phi - 1) - \Delta\phi \sin\phi\right\} + \Delta H_e \cos\phi + \left\{(H_o + \Delta H_o)\cos(\theta + \Delta\theta) - H_o \cos\theta\right\}$$

provided $\Delta\phi$ is kept small. The terms in H_o and ΔH_o are the ones of geophysical interest and represent the anomalous field to be measured, while ΔH_e is a term whose approximate value can be calculated from Earth's unperturbed magnetic

field if ϕ is known.

The terms in H_e vanish only if $\Delta\phi$ is zero and hence may be called orientation errors. Since H_e is of the order of 50,000 gammas, $\Delta\phi$ must be kept quite small. In the design of the MAD systems AN/ASQ-1, AN/ASQ-3, and AN/ASQ-3A, the angle ϕ is kept near zero so that the inductor is approximately parallel to Earth's total field, H_e. In this least stringent case, $\Delta\phi$ may be as large as 0.3 degrees for a corresponding error of one gamma in ΔH. In the worst case (which can occur if the inductor is oriented by a pendulum or gyroscope), ϕ is 90° and $\Delta\phi$ must be smaller than 10^{-3} degrees if the error in ΔH is to be less than one gamma.

An inductor mounted on a gyroscope can be made sufficiently stable for a short period to detect an anomaly when the inductor is carried across it. However, all small gyroscopes presently available are insufficiently stable to keep the orientation error $\Delta\phi$ within an order of magnitude of the limits indicated above for a time sufficiently long to permit an appreciable area to be mapped.

Three mutually perpendicular inductors can be used to measure small field changes ΔH in terms of scalar energy of the field, since $\Delta H^2 = 2H\Delta H$. However, a system of three mutually perpendicular inductors arranged to measure $H^2 = {H_1}^2 + {H_2}^2 + {H_3}^2$, does not approach the required mechanical and electrical precision and stability for geophysical applications unless one of the three inductors is nearly parallel to the total field vector H. The latter case is of interest in the design of the modified MAD system AN/ASQ-3A.

Let inductor number 1, originally parallel to the total field vector H, be displaced through a small polar angle $\Delta\phi$. If α is the azimuthal angle of the displacement projected on the plane of inductors numbered 2 and 3, then

$$\Delta H_1 = H(\cos\ \Delta\phi - 1) = -H(\Delta\phi)^2/2$$

$$\Delta H_2 = H \cos\alpha \sin\Delta\phi = \Delta\phi\ H \cos\alpha$$

$$\Delta H_3 = H \sin\alpha \sin\Delta\phi = \Delta\phi\ H \sin\alpha$$

$$\Delta H_1 = -[(\Delta H_2)^2 + (\Delta H_3)^2]/2H$$

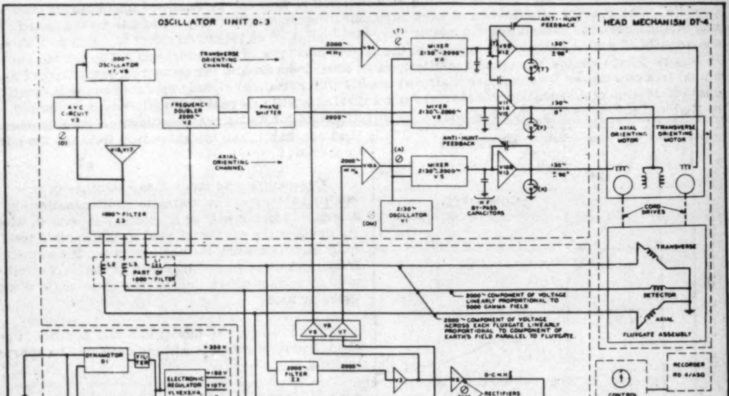
OSCILLATOR UNIT O-3
1000~ OSCILLATOR V7, V8
A V C CIRCUIT V3
(D)
V16, V17
1000~ FILTER Z3
FREQUENCY DOUBLER 2000~ V2
PHASE SHIFTER
TRANSVERSE ORIENTING CHANNEL
AXIAL ORIENTING CHANNEL
2000~
V9A
V10A
(T)
(A)
MIXER 2130~-2000~ V4
MIXER 2130~-2000~ V6
MIXER 2130~-2000~ V5
2130~ OSCILLATOR V1
(OM)
ANTI-HUNT FEEDBACK
V9B V12
V11 V14 V15
V10B V13
H F BY-PASS CAPACITORS
130~ ±90°
130~ 0°
HEAD MECHANISM DT-4
AXIAL ORIENTING MOTOR
TRANSVERSE ORIENTING MOTOR
CORD DRIVES
TRANSVERSE
DETECTOR
AXIAL
FLUXGATE ASSEMBLY
L1 L2 L3
PART OF 1000~ FILTER
2000~ COMPONENT OF VOLTAGE LINEARLY PROPORTIONAL TO 5000 GAMMA FIELD
2000~ COMPONENT OF VOLTAGE ACROSS EACH FLUXGATE LINEARLY PROPORTIONAL TO COMPONENT OF EARTH'S FIELD PARALLEL TO FLUXGATE
V8 V6 V7
DYNAMOTOR D1
DYNAMOTOR D2
FIL-TER
ELECTRONIC REGULATOR V1, V2, V3, V4, V5, V6
REGULATION ADJUSTMENT
+330 V
+180 V
+107 V
-B
+28 V
+12 V
-A
28 V
(ON-OFF)
V7
2000~ FILTER Z3
2000~ FILTER Z2
2000~ FILTER Z1
V3
V2
V1
V4
V5
RECTIFIERS
(CT)
(CA)
D-C ∝ H²
D-C EQUIV TO 3000 GAMMAS ABOVE EARTH'S FIELD
TRANSFORMER T1
RECTIFIER
V9 V10
(C)
CONTROL BOX C-83
RECORDER RD 4/ASQ
D-168034 ID-40
INDICATING METERS
DYNAMOTOR UNIT DY-6
CONVERTER UNIT CV-3

Fig. 6--Block diagram of AN/ASQ-3A equipment

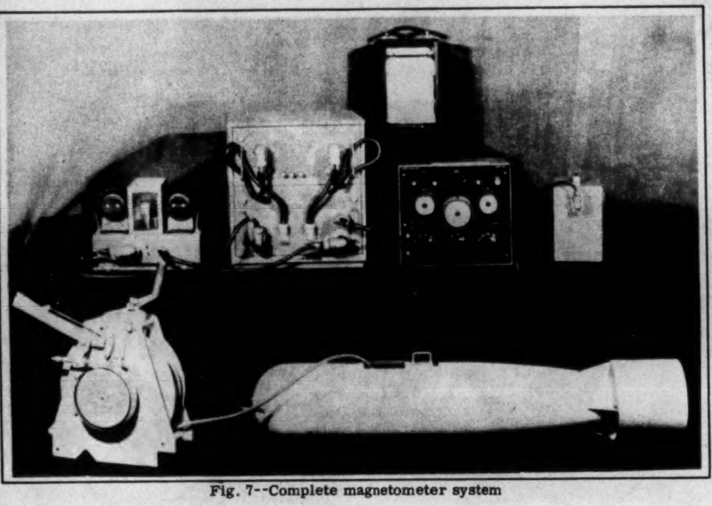

Fig. 7--Complete magnetometer system

If $\Delta\phi$ is two degrees, or less, the correction term ΔH_1 needs to be accurate only to about three per cent to keep the error below one gamma.

The MAD system AN/ASQ-3A (modified for geophysical mapping)--The MAD system AN/ASQ-3A, Figures 6 and 7, has been described in detail elsewhere [OTS, 1946], and only the principal features will be outlined here.

Refer to Figure 6. Current from a regulated 1000 cps oscillator is passed through a 1000 cps band-pass filter to each of three mutually perpendicular saturable inductors, called the detector, axial, and transverse inductors. The second harmonic signal emf from each inductor is passed through a narrow band-pass filter (mid-band frequency 2000 cps) before further use.

The detector inductor is kept approximately parallel to the total field vector. The 2000 cps signal from the detector inductor is amplified, rectified linearly, and passed into a control box. The control box contains a battery and a manually controlled resistance network through which an appropriate constant d-c suppression current is passed back to the detector inductor. The suppression current is set so that the resultant field applied to the detector element is approximately 1500 gammas above the Earth's total field in the region under survey. Finally, the rectified field signal from the detector inductor is passed from the control box to the recorder and to such indicating meters as are desired.

The 2000 cps signals from the transverse and from the axial inductor represent small inductor orientation errors and are used to perform two functions, namely; (1) 2000 cps voltages proportional to the misalignment signals in the axial and transverse inductors are heterodyned against a 2130 cps oscillator and then applied to the windings of servo-motors to rotate the detector around axes of a gimbal mechanism, Figure 8, in a manner tending to return the axial and transverse inductors to positions of zero signal, so that the axial and transverse inductors both are kept approximately perpendicular to the total field vector; (2) each 2000 cps error emf also is amplified and rectified parabolically to produce a d-c voltage proportional to the square, $(\Delta H_2)^2$ or $(\Delta H_3)^2$, of the error field. The combined output currents from the two squaring rectifiers are passed into and subtracted from the suppression current to the detector inductor so that this inductor, in effect, receives an additional signal ΔH_1 to compensate for misalignment.

Since the error compensating current must be inversely proportional to the total field H, as well

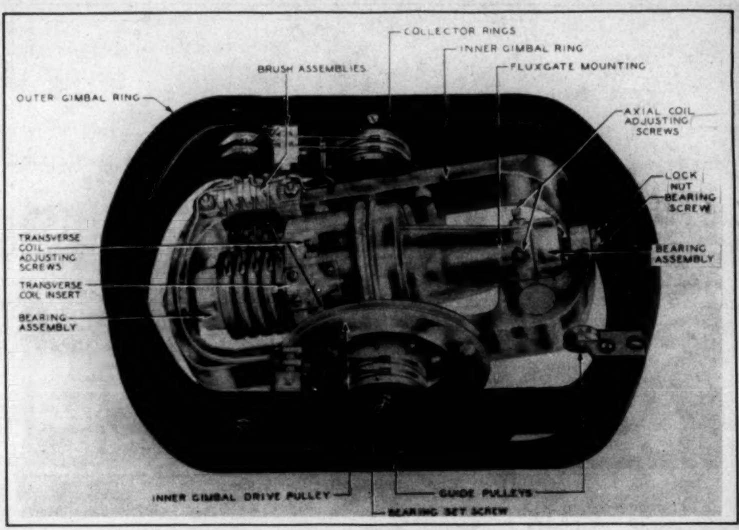
COLLECTOR RINGS
INNER GIMBAL RING
BRUSH ASSEMBLIES
FLUXGATE MOUNTING
OUTER GIMBAL RING
AXIAL COIL ADJUSTING SCREWS
LOCK NUT
BEARING SCREW
BEARING ASSEMBLY
TRANSVERSE COIL ADJUSTING SCREWS
TRANSVERSE COIL INSERT
BEARING ASSEMBLY
INNER GIMBAL DRIVE PULLEY
GUIDE PULLEYS
BEARING SET SCREW

Fig. 8--Gimbal mechanism

as proportional to the sum of the squares of the error fields, this current is passed through a resistance kept proportional to the mean local total field by ganging with the suppression field control.

The complete magnetometer system AN/ASQ-3A is shown in Figure 7, together with a streamlined nacelle or "bird" for housing the inductor assembly, and a winch and cable for streaming and retrieving the bird. The approximate weight of this equipment, including the winch and bird, is 320 l and the volume is about ten cubic feet. The equipment may be broken into units for installation in the plane, since only access to the control box and winch is required during flight.

Instrumentation for geophysical exploration with MAD--The objective of aerial magnetic surveys is to construct reliable isomagnetic contour maps of extensive areas. The associated instrumental requirements, as originally set by the Naval Ordnance Laboratory and the United States Geological Survey, have been extended and verified by experience covering essentially all conditions likely to be encountered in aerial exploration. The desirable functional specifications for general purpose surveying may be stated as follows:

(1) The combined instrumentation should be sufficiently sensitive and stable to give an over-all reliability of about ± two gammas between adjacent isomagnetic contours.

(2) Continuous records of magnetic field and plane position and altitude should be provided and correlated automatically.

(3) Positive flight control should be established to guide the pilot and plane along predetermined flight lines of a network covering the area.

(4) Visual indicators of survey progress and equipment functioning should be furnished to operators in the plane.

(5) A record of magnetic field fluctuations should be taken at a ground station.

(6) The absolute value of the local magnetic field need not be known more closely than ± one per cent, but measurements of departures from this arbitrary value must be made with precisions of one or two gammas.

A relative precision of two gammas or better between adjacent isomagnetic contours is desirabl in mapping low gradient areas and in detecting the small anomalies associated with thin structures disposed at unfavorable angles with Earth's magnetic field. This accuracy implies that each of the four principal magnetic errors should be held below one gamma. These four sources of error are: (1) magnetometer noise and drift; (2) geomagnetic gradients; (3) vehicular magnetization; and (4) fluctuations in the terrestrial field, including random departure from the assumed known value of magnetic field at a check point or along a base line.

It is not unreasonable to allocate about one-half gamma to the random instrumental noise of a magnetometer in flight and to keep uncertainties due to the magnetometer's drift down to about the same value. Since it is impractical to use extremely short flight lines in aerial mapping, this means that the drift should be kept to about ten gammas per hour and be reasonably linear with time, in order to permit flights of, say, 20 mi away from a base line or check point whose magnetic field is known. These requirements have been met in the airborne magnetometer AN/ASQ-3A (modified).

The geomagnetic field exhibits the general magnetic gradients characteristic of the field of a dipole at the center of the Earth. The vertical gradient of the total field varies from about four gammas per thousand feet near the geomagnetic equator to roughly nine gammas per thousand feet at the poles. The horizontal gradient along a meridian has a peak value of around ten gammas per mile. For combined position errors less than one gamma, this requires that position along a magnetic meridian should be known within about 300 ft and that altitude should be measured as closely as 100 ft, independent of any further precision required for the interpretation of an anomaly. A somewhat arbitrary combination of the above factors has indicated the desirability of fixing the airplane position within a 100-ft cube in flight records for the more precise surveys.

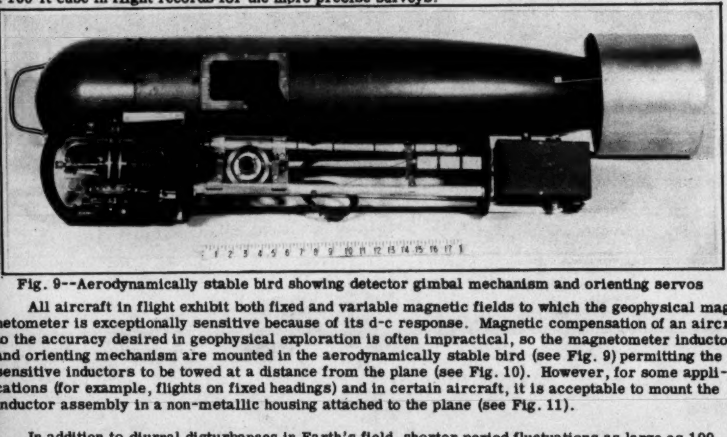

Fig. 9--Aerodynamically stable bird showing detector gimbal mechanism and orienting servos

All aircraft in flight exhibit both fixed and variable magnetic fields to which the geophysical magnetometer is exceptionally sensitive because of its d-c response. Magnetic compensation of an aircraft to the accuracy desired in geophysical exploration is often impractical, so the magnetometer inductors and orienting mechanism are mounted in the aerodynamically stable bird (see Fig. 9) permitting the sensitive inductors to be towed at a distance from the plane (see Fig. 10). However, for some applications (for example, flights on fixed headings) and in certain aircraft, it is acceptable to mount the inductor assembly in a non-metallic housing attached to the plane (see Fig. 11).

In addition to diurnal disturbances in Earth's field, shorter period fluctuations as large as 100 gammas may occur frequently at high latitudes. The obvious monitor for correcting flight data is a ground station equipped with a recording magnetometer similar to the one carried by the airplane. Fluctuations in the air or at points above a base line will not necessarily be the same as at the ground station, so interruption or postponement of the survey may be advisable if the fluctuations approach, say, five gammas during a 15-min period. The fluctuations which can be tolerated will depend, of course, on the flight time between base line check points and the precision desired in the survey.

In aerial magnetic surveys over land, sufficient guidance for the pilot and plane can be supplied by an observer equipped with an aerial photographic map on which flight lines have been laid out and landmarks have been identified in advance. Both an aneroid and a radio altimeter may be required for flight control and record.

In present Naval Ordnance Laboratory-United States Geological Survey practice [JENSEN and BALSLEY, 1946], the records for surveys over land consist of a continuous strip photograph of the terrain below the plane, a continuous radio altimeter record, and a continuous magnetometer record (see Fig. 12). The latter two records are taken on the tapes of recording milliammeters equipped with edge-marking pens. All records receive edge-marks simultaneously and at frequent intervals, par-

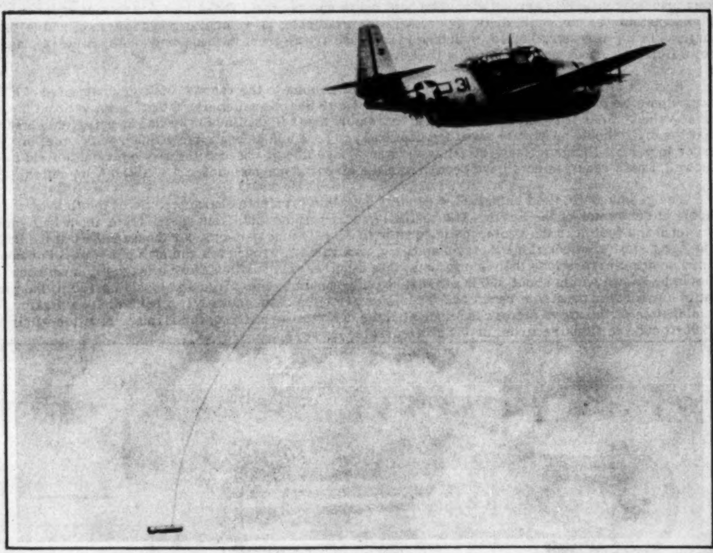

Fig. 10--Towed bird installation

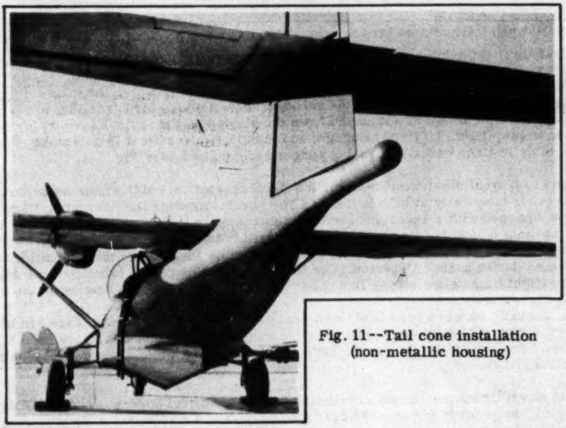

Fig. 11--Tail cone installation (non-metallic housing)

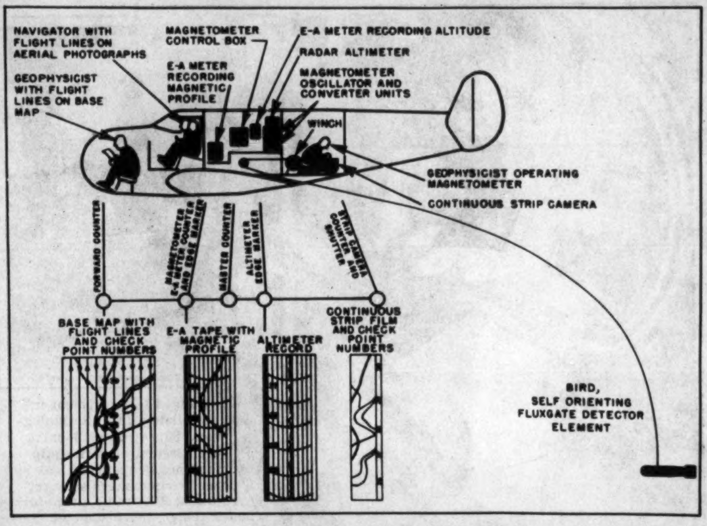
NAVIGATOR WITH FLIGHT LINES ON AERIAL PHOTOGRAPHS
GEOPHYSICIST WITH FLIGHT LINES ON BASE MAP
MAGNETOMETER CONTROL BOX
E-A METER RECORDING MAGNETIC PROFILE
E-A METER RECORDING ALTITUDE
RADAR ALTIMETER
MAGNETOMETER OSCILLATOR AND CONVERTER UNITS
WINCH
GEOPHYSICIST OPERATING MAGNETOMETER
CONTINUOUS STRIP CAMERA
FORWARD COUNTER
MAGNETOMETER E-A METER COUNTER AND EDGE MARKER
MASTER COUNTER
ALTIMETER EDGE MARKER
STRIP CAMERA COUNTER AND SHUTTER
BASE MAP WITH FLIGHT LINES AND CHECK POINT NUMBERS
E-A TAPE WITH MAGNETIC PROFILE
ALTIMETER RECORD
CONTINUOUS STRIP FILM AND CHECK POINT NUMBERS
BIRD, SELF ORIENTING FLUXGATE DETECTOR ELEMENT

Fig. 12--Schematic of flight control instrumentation

ticularly when the plane is passing over a landmark. A serial number corresponding to each successive edge-mark is provided by number-counters and is automatically stamped on each milliammeter record and superimposed on the strip photograph. In addition, flexible shaft connections to the magnetometer control box automatically stamp the new setting on the magnetometer tape whenever the magnetometer sensitivity or the reference field (suppression current) is changed. Figure 13 shows the interior of a United States Geological Survey plane in which this equipment is installed.

In flights over water, visual contact flight control is replaced by Shoran control for maintaining successive flight paths along circular arcs of constant distance from a drift station. Shoran measures distance in terms of the time required for a radio pulse to travel from the aircraft to a fixed station and return to a receiver in the plane. The pilot is guided by an error indicator driven from the Shoran receiver to show the amount and direction of departures from course by right or left deflections of a needle (see Fig. 14). A recording milliammeter connected to the Shoran receiver continuously registers the pilot's error (amount of departure from the course) on a tape. Position along each circular arc is given by the distance from a second Shoran station called the rate station. When the plane opens or closes with the rate station, the Shoran operator keeps pace by turning distance dial for the rate station. The pilot's error record and the magnetometer record are edge-marked automatically at each successive one-mile turn of the distance dial for the rate station. A check against erratic rate station dial adjustment by the Shoran operator is provided by a foot-switch to edge-mark the other side of the pilot's error-record tape when the rate-station "pip" and the reference "pip" coincide on the Shoran oscilloscope screen. A stamping system for recording serial numbers and control-box settings can be provided in the same manner as for flights over land.

Reduction of data--The first step in planning the survey of an area consists in drawing a grid or network of flight lines to cover the area in the detail desired for the magnetic map. Next, several flight lines are chosen as base lines. Each base line is flown twice, in opposing directions, to determine instrument drift. The base lines are chosen so that all flight lines will cross them frequently (approximately every fifteen minutes). From the flight records, accurate magnetic profiles are constructed for each flight line. Drift corrections are made and the zero of each profile is adjusted to fit the base line data. Isomagnetic lines are then drawn to complete the contour mapping.

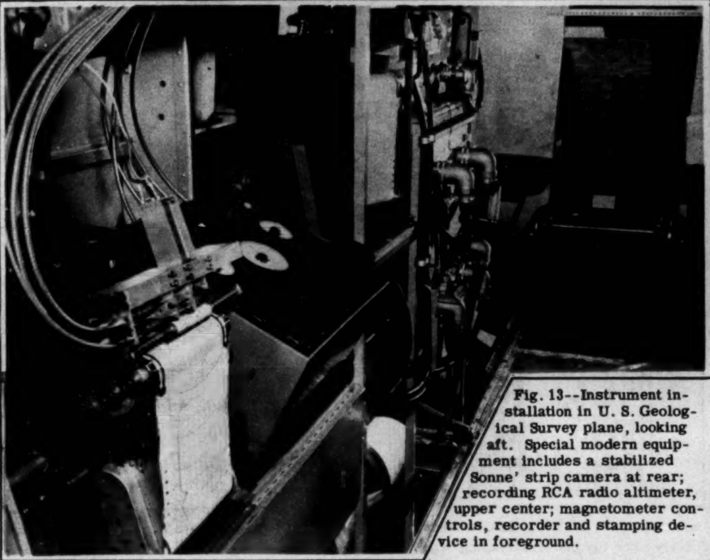

Fig. 13--Instrument installation in U. S. Geological Survey plane, looking aft. Special modern equipment includes a stabilized Sonne' strip camera at rear; recording RCA radio altimeter, upper center; magnetometer controls, recorder and stamping device in foreground.

Many surveys of this type have been completed by both the Government and several commercial companies. Descriptions of and the results of several such surveys can be found in the literature [DUDLEY, 1947; JENSEN, 1949; ALLDREDGE and KELLER, 1949; ALLDREDGE and DICHTEL, 1949].

Future airborne magnetometers--The magnetometer described above has served admirably for geophysical prospecting where a total field intensity contour map was considered adequate. There is a great need, however, for an airborne magnetometer which can determine the entire magnetic vector in space and thereby permit calculation of all components. Such a device would be especially valuable for use as a survey instrument for obtaining new data for world-wide magnetic charts. The AN/ASQ-3A is being further modified at the Naval Ordnance Laboratory to convert it into such an instrument.

Angle measuring potentiometers are being added to the gimbal mechanism (see Fig. 8) to permit the recording of the direction of field relative to the aircraft frame. Additional equipment is being designed to automatically record the pitch and roll of the aircraft frame with respect to vertical and its orientation with respect to true north.

It is still too early to be sure of the final accuracy which can be achieved by this new instrument but it is hoped that the derived component measurements will approach the accuracy which was possible on the old non-magnetic ships such as the Carnegie. This instrument will be ready for flight testing in the very near future.

Summary--The modified airborne magnetometer AN/ASQ-3A and the systems of flight-record instruments developed by the Naval Ordnance Laboratory have been used successfully in cooperation with the United States Geological Survey, the Office of Naval Research, and the Naval Petroleum Reserves in mapping areas which now total about a half million square miles. This experience has included both low and high gradient fields; land and offshore areas; mountains, plains, deserts, atolls and open ocean; and Alaskan and Antarctic operations. It has been demonstrated

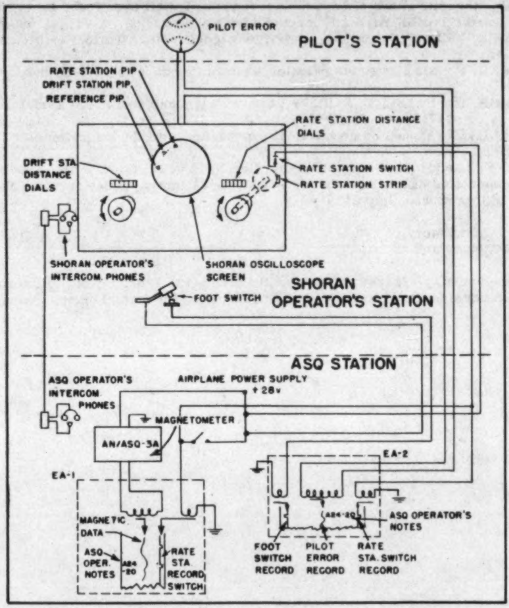
PILOT ERROR
PILOT'S STATION
RATE STATION PIP
DRIFT STATION PIP
REFERENCE PIP
RATE STATION DISTANCE DIALS
DRIFT STA DISTANCE DIALS
RATE STATION SWITCH
RATE STATION STRIP
SHORAN OPERATOR'S INTERCOM. PHONES
SHORAN OSCILLOSCOPE SCREEN
FOOT SWITCH
SHORAN OPERATOR'S STATION
ASQ STATION
ASQ OPERATOR'S INTERCOM. PHONES
AIRPLANE POWER SUPPLY +28v
MAGNETOMETER
AN/ASQ-3A
EA-1
EA-2
MAGNETIC DATA
ASQ OPER. NOTES
A24-20
RATE STA. RECORD SWITCH
A24-20
ASQ OPERATOR'S NOTES
FOOT SWITCH RECORD
PILOT ERROR RECORD
RATE STA. SWITCH RECORD

Fig. 14--Schematic of shoran flight-control instrumentation

that the system of instruments and associated procedures, as described in the present paper, are adequate for the construction of reliable charts of total magnetic field. Measurements are made in terms of changes in total field along flight lines departing from a base point at which the absolute value of total field is known or assumed. Dependability of the mobile magnetometer is indicated by closure errors. In general, closure errors less than ten gammas are obtained on flights at about 100 knots around the periphery of a square with 50-mi sides. The system has been chiefly used in intensive surveys (geophysical exploration) for the preparation of isomagnetic contour maps of anomalies. Typical low gradient anomalies can be covered at rates of 500 to 1000 sq mi per flight day with flight lines spaced one to two miles apart. Resulting isomagnetic contour maps are usually dependable to ± two gammas. The system is equally useful in the preparation of total field charts of less exactness in which extended geomagnetic measurements are obtained by either wide-spaced grid or open flight line methods. The AN/ASQ-3A system is being further modified to make it capable of recording the entire magnetic vector field rather than just the field intensity.

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SURF BEATS

W. H. Munk

(Contribution from the Scripps Institution of Oceanography, New Series, No. 434)

__Abstract__--Irregular oscillations of the near-shore water level, with periods of the order of several minutes, are correlated with fluctuations in the height and period of incoming waves.

An instrument for recording long-period ocean waves [MUNK, IGLESIAS, and FOLSOM, 1948] has been in operation since January 1948 at the end of the Scripps Institution pier, La Jolla, California. The instrument, which is sensitive to waves whose frequencies fall between those of the wind-generated waves and those of the astronomic tides, is called the tsunami recorder, as it is especially adapted to the period range of tsunamis. In the presence of high wind waves the tsunami recorder reveals irregular oscillations of several minutes' period. These oscillations have a broad frequency spectrum, which reaches a maximum in amplitude for periods of the order of two minutes, and drops off for longer and shorter periods by about six decibels per octave.

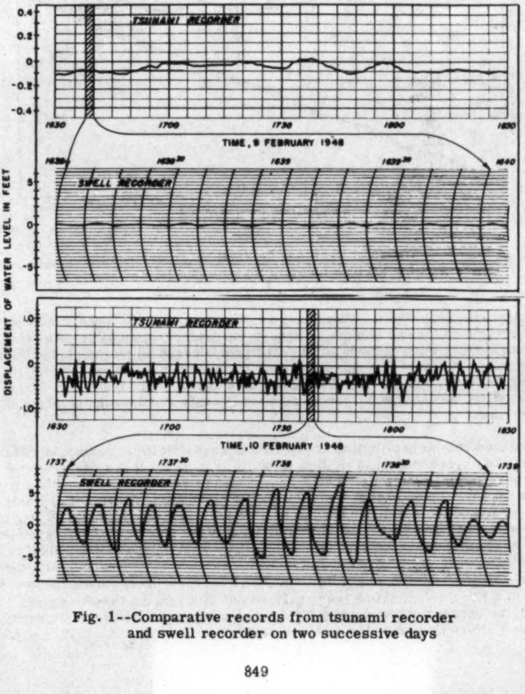

Fig. 1--Comparative records from tsunami recorder and swell recorder on two successive days

Figure 1 shows comparative records taken on two successive days by the tsunami recorder and by a swell recorder [FOLSOM, 1949]. The time scales bear a ratio of 60:1, and the shaded band on the tsunami record shows the duration of the swell record. The height scales on the tsunami and swell records refer to periods of two minutes and eight seconds, respectively. The swell recorder is about equally responsive to waves of eight-second and two-minute periods, whereas the tsunami recorder is forty times as responsive to the two-minute waves as to the eight-second waves. The swell recorder is located 1000 ft off the end of Scripps Pier in water of about 40-ft depth, (see Fig. 2); it records pressure fluctuations at the sea bottom against time, and these can be interpreted in terms of the oscillations of the sea surface. Both instruments are connected by electric cables to a building ashore where the waves are recorded. On the afternoon of February 9 the sea was glassy calm (wave heights less than three inches), and the tsunami record smooth, except for two-inch undulations of approximately 20-min period, which are typical of certain meteorological conditions off the coast of California. Twenty-four hours later the swell recorder showed waves of seven- to nine-second period up to ten feet in height, and the tsunami recorder revealed irregular two- to three-minute oscillations up to 0.8 feet in height.

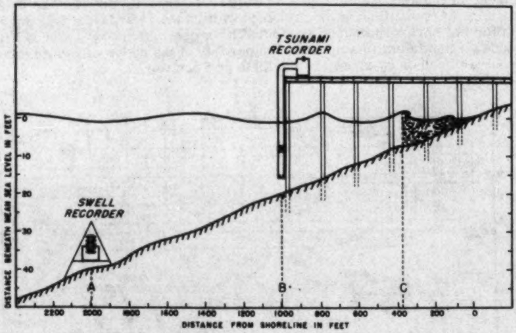

Fig. 2--Location of swell and tsunami recorders relative to the Scripps Institution pier at La Jolla

Figure 3 shows the height of the significant waves (average of the highest one-third) on the tsunami and swell recorders for two storms. Although the determination of the numerical values of significant wave height from wave records is subject to some personal judgment, the figure indicates a definite relationship between wave heights recorded by the two instruments. From 103 measurements conducted during February and March, 1948, (see Table 1) it appears that at the Scripps Institution pier on the average the height of wind-generated waves equals 11 times the height of the waves on the tsunami recorder.

The two- to three-minute oscillations are related to the variability in the height and period of the incoming waves. To anyone wading in shallow water it is apparent that a rapid succession of high breakers temporarily raises the water level. John Isaacs (personal communication) has observed such changes in sea level up to 16 ft at Twin Rocks Beach, Oregon. To investigate this quantitatively, we note that according to the solitary wave theory [MUNK, 1949] the volume of water transported into the surf zone by each breaking wave is proportional to the square of the breaker height. On a 20-min section of swell record (see Fig. 4) starting at $t = 0$ ($11^h 02^m 20^s$) and ending at $t = 1080$ sec ($11^h 20^m 20^s$) the wave crests are numbered 1, 2, . . .n, . . .N. Let n designate the nth wave arriving at a time t_n and having a height H_n. The shoreward transport during the interval O to t_n is proportional to $\sum_n H_n^2$, the summation being carried out with respect to wave crests. For the entire 20-min interval, the shoreward transport $\sum_N H_n^2$ must equal approximately the seaward transport due to a superimposed return flow, rip currents, and other processes [MUNK, 1949]. Assume the seawar transport to be constant with time. Then

$$\sum_n H_n^2 - (n/N)\sum_N H_n^2$$

Table 1--Comparative heights of waves on tsunami recorder (period two to three minutes) and swell recorders (period seven to nine seconds)

Range in wave height	Number of measurements	Significant wave height		Ratio $\frac{\text{Col 4}}{\text{Col 3}}$
		Tsunami recorder	Swell recorder	
1	2	3	4	5
ft		ft	ft	
<1	15	.085	0.8	9.5
1 - 2	36	.15	1.6	10.7
2 - 3	24	.20	2.6	13.0
>3	28	.35	4.6	13.1
Weighted mean				11.4

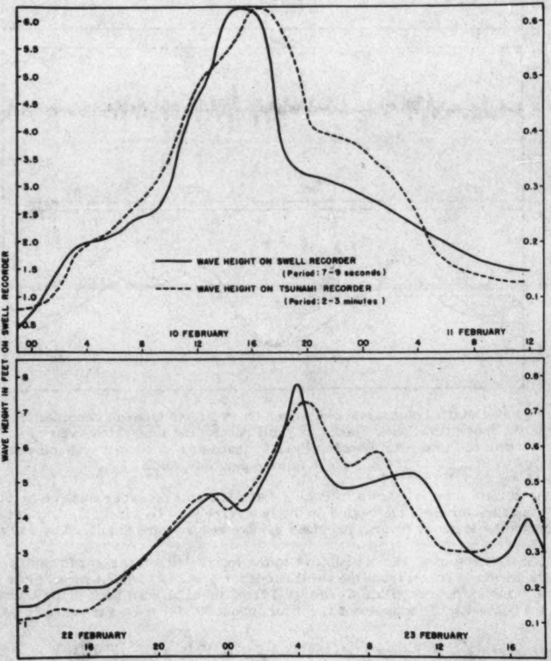

Fig. 3--Comparative heights of waves shown by the tsunami and swell recorders for two storms; the height scale on the tsunami record is exaggerated ten times relative to the height scale on the swell records represents the excess (in arbitrary units) of the shoreward transport over the seaward return between the times 0 and t_n. This quantity is marked "integrated swell record" in Figure 4.

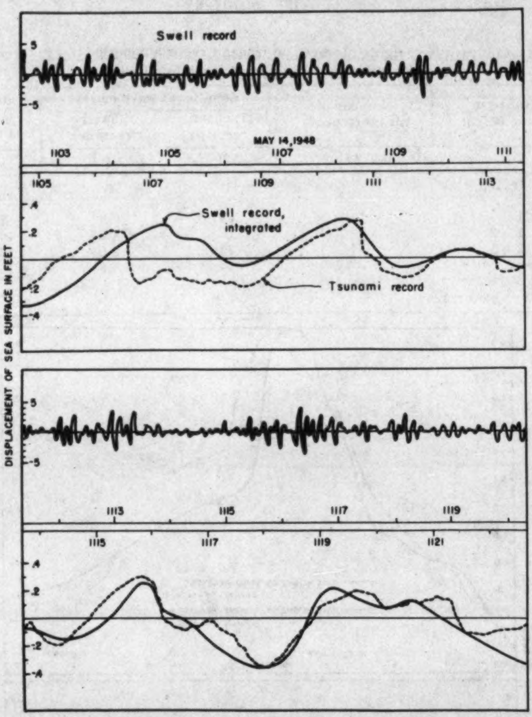

Fig. 4--Detailed comparison of waves on swell and tsunami recorders; the upper time scale refers to swell record and integrated swell record; the lower time scale refers to tsunami record, and is displaced 140 sec relative to upper time scale

During the 20-min interval shown in Figure 4 the tsunami recorder was run at 60 times its normal speed in order for the time scales on the two records to be identical. The integrated swell record resembles the tsunami record, provided the two records are displaced by 140 sec.

This lag Δt of the tsunami record relative to the integrated swell record results from the time involved for the waves to travel from the swell recorder past the tsunami recorder to the surf zone, for the two- to three-minute oscillations to travel from the surf zone back to the tsunami recorder (Fig. 2), and the phase lag of the tsunami recorder, about 90° for waves of two-min periods. Thus

$$\begin{aligned}\Delta t &= \int_A^B (1/V)dx + \int_B^C (1/V)dx + \int_C^B (1/V)dx + (90^\circ/360^\circ)120 \\ &= \quad 42 \quad + \quad 34 \quad + \quad 30 \quad + \quad 30 \quad = 136 \text{ seconds}\end{aligned}$$

Table 2--Computed horizontal orbital velocities, displacements, and pressure fluctuations at ocean bottom associated with waves of eight-second period and 4.5-ft height in deep water, and with surf beats of two-minute period caused by these waves

Depth	Height		Horizontal orbital velocity		Horizontal displacement		Pressure	
	Waves	Surf beat	Waves	Surf beat	Waves	Surf beat	Waves	Surf beat
ft	ft	ft	ft/sec	ft/sec	ft	ft	ft/sea water	ft/sea water
7.5[a]	6.0	0.6	5.9	0.62	15	24	5.6	0.60
10	5.2	0.5	4.4	0.45	11	17	4.7	0.50
20	4.5	0.47	2.5	0.30	6.4	11	3.7	0.47
50	4.2	0.39	1.1	0.16	2.8	6.1	2.4	0.39
100	4.3	0.31	4.7×10^{-1}	0.088	1.2	3.4	1.2	0.31
200	4.5	0.26	8.0×10^{-2}	0.052	2.0×10^{-1}	2.0	1.9×10^{-1}	0.26
500	4.5	0.21	1.2×10^{-4}	0.027	3.1×10^{-4}	1.0	3.0×10^{-4}	0.21
1000	4.5	0.18	8.1×10^{-9}	0.016	2.0×10^{-8}	0.6	2.1×10^{-8}	0.18

[a] Breaking point

compared to a measured time lag of 140 sec. The values have been obtained by numerical integration, setting eight seconds and two minutes for the periods of incoming and outgoing waves, respectively, and substituting

$$V = \sqrt{(g \tanh kh)/k}\,(1 + 2kh/\sinh 2kh)/2$$

for the group velocity of waves of length $2\pi/k$ at depth h. The distances are those shown in Figure 2. The seaward boundary of the surf zone was determined by the wave dimensions at $11^h\ 00^m$ on May 14, 1948; period, eight seconds; deep water height, 4.5 feet; breaker height, six feet; depth of breaking, 7.5 feet. If the fluctuations of the tsunami record had been the result of a non-linearity in response of the instrument, the time lag would have been 42 + 30, or 72 sec, approximately half the measured time lag.

In view of the 1000 ft distance separating the swell and tsunami recorders and of other uncertainties, the agreement between the integrated swell record and the tsunami record (see Fig. 4) and between the computed and observed time lag are as good as one might expect. The two- to three-minute oscillations shown by the tsunami recorder appear to be caused by the variability of water transport into the surf zone, and are therefore termed "surf beat." Fluctuations in the speed of longshore currents and rip currents [PUTMAN, MUNK, and TRAYLOR, 1949; SHEPARD and INMAN, in press] are due to the same condition. The variability of the breaking waves results from the variability in the height and period of the waves offshore, and this variability in turn depends essentially on the ratio of storm size to storm distance, and is relatively small for compact storms at large distances.

The shore line acts therefore as a radiating line source which returns approximately one per cent of the incoming wave energy in the form of long-period waves. This is characteristic of the reaction of non-linear systems to high incoming waves. Indeed the surf zone may be considered an extreme case of non-linearity.

The amplitudes of orbital velocity and pressure fluctuation and the double amplitude of horizontal displacements at the sea bottom have been computed for the conditions shown in Figures 2 and 4, assuming the surf beat to travel seaward and being modified according to the usual theory [LAMB, 1932, and U. S. HYDROGRAPHIC OFFICE, 1944]. Results are summarized in Table 2. For depths exceeding 200 ft the greater length of the surf beat more than compensates for its smaller height; at a depth of 500 ft, a typical depth for the outer edge of the continental shelf, the surf beat is associated with 200 times the orbital velocity, and 70 times the pressure fluctuation of that of the incoming waves. At mid-depth in water of 1000-ft depth the vertical accelerations associated with the surf beat and the waves are both approximately 3×10^{-6}g. The surf beat may be the cause of short-period internal waves, and of surges in harbors.

Acknowledgment--This work represents results of research carried out for the Office of Naval Research, the Hydrographic Office, and the Bureau of Ships of the United States Navy Department under contract with the University of California.

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STABLE CONFIGURATION OF BOTTOM SLOPE IN A SHALLOW SEA AND ITS BEARING ON GEOLOGICAL PROCESSES

G. H. Keulegan and W. C. Krumbein

Abstract--Wave action is a major factor in the formation of beaches and major shore features. However, there are sedimentary formations apparently having their origin in shallow seas in the absence of wave action. This could occur if the bed sloped upward very gently from a moderate depth to the shore line so that the waves approaching the shore were gradually modified in shape and energy content, arriving with zero energy and without breaking anywhere. A mathematical analysis of the problem is made on the assumption that the slope of the bed is such that the waves move shoreward with their maximum possible height without breaking. The bed profile which will accomplish this is computed, and the geological implications of the theory are presented

Introduction--Widespread sedimentary formations with marine fossils attest to repeated inundations of large parts of the continents by marine waters in the geological past. In parts of North America these sediments display remarkable uniform characteristics and often carry evidence of relatively shallow-water deposition. This evidence includes ripple marks, cross-bedding, and other features which suggest that the depths did not exceed a few scores of feet over large areas. These broad epicontinental seas are believed to have invaded the continents from the margins or by way of large geosynclines, from which they spread over the more stable part of the continental platform.

Beaches and other major shore features form when sufficient energy is concentrated along the strand to operate upon the material present. The energy may be utilized in part by cutting sea cliffs, and in part by removing and redepositing the eroded material into beaches, bars, and other features. If no appreciable wave energy is available, either owing to absence of wave action, or because the waves dissipate their energy over a wide expanse of sea bottom instead of along a relatively narrow breaker zone, typical shore features may not be developed.

Studies of ancient sedimentary deposits show numerous coarse pebble conglomerates and other features which indicate the operation of shore agents along the margins of the ancient seas but in other instances there is no clear evidence that important wave action occurred along the shorelines. It seems likely that typical wind waves were present in all ancient seas, but it may have been true that under certain physical conditions the waves dissipated their energy before striking the shore, with the result that typical shore deposits are absent from the sediments left behind.

A consideration of the factors involved in energy dissipation suggested that it should be possible to define critical conditions under which wave action may be absent along exposed shores due to dissipation of the waves as they approach it. The critical conditions may then be examined to see whether they apply in nature. The mathematical development in this paper is the work of the first author, and the geological implications are by the second author.

Theoretical development--The problem treated in this section considers a shallow sea with bottom slope from moderate water depths to the strand line so gentle that waves which approach the shore are continually modified in shape and energy content so that they reach the shore with essentially zero energy, and without breaking at any point along their path to the shore. The conditions include an offshore area remote from the land in which wind waves may be developed to whatever height and length are appropriate to the conditions at sea. These waves move toward the shore over the gently sloping bottom, and the problem is to determine the critical bottom slope which will assure complete energy dissipation without breakers. The critical bottom slope may have been present at the time the sea encroached upon the continental platform; or the agencies involved may tend to develop such a critical slope by a shift of bottom materials. Once attained, the slope remains stable as long as the given geological conditions persist.

For purposes of simplifying the mathematical analysis, ordinary shallow water waves may be considered as consisting of a series of solitary waves moving in a current that has velocity equal and opposite to the mean water velocities in the troughs of the actual waves. The approximate value of the current can be obtained by supposing that the forward motion of the waves results in no net accumulation of water between any selected point and the shoreline. Let u_t be the velocity of the current and u the water particle velocity along any vertical section through the wave with reference to the main current. As there is no accumulation of water, the flux across a section during unit time equal to the wave period must vanish. Approximately

$$\int_0^\lambda H\,(u + u_t)dx = 0 \qquad (1)$$

where H is the depth of water in the troughs, λ is the wave length (the distance between two successive crests), and dx is a unit distance along the direction of wave motion. The approximation in (1) ignores the surface differential elevation h in computing the vertical areas. In a rigorous development, H must be replaced by H + h. As a first approximation the velocities in the elevated portion of the wave may be given by

$$u = (h/H)\sqrt{gH} \qquad (2)$$

as shown in Figure 1.

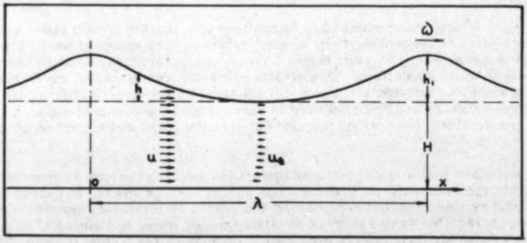

Fig. 1--A wave train in shoal water considered as a series of solitary waves moving against a current

Assuming that the elevated portions of the waves may be approximated by the forms of solitary waves, then

$$h = h_1 \ \mathrm{sech}^2 kx \qquad (3)$$

where h_1 is the crest height above the troughs and k has the value

$$k = \sqrt{3h_1/4H^3} \qquad (4)$$

These results are sufficiently well known not to require discussion [KEULEGAN, 1948]. In terms of these relations the integration of (1) leads to

$$u_t = -(2H/\lambda)\sqrt{4gh_1/3} \qquad (5)$$

The bottom velocities $u + u_t$ may now be written as

$$U_0 = (h_1/H)\sqrt{gH}\ \mathrm{sech}^2 kx - (2H/\lambda)\sqrt{4gh_1/3} \qquad (6)$$

and may be used to obtain the velocities under the conditions that the wave length is large compared to the water depth.

If bottom velocities are computed by (6) for given values of H, λ, and h_1, it is found that the bottom velocities for one part of the wave period are positive in value and for the remaining part, which is the greater of the two, they are negative. A sand particle lying on a smooth surface would experience a forward and backward force, and in general it would experience a resultant forward force with the passage of two successive troughs. Actual movement of the sand particle will depend in part on its size and on the wave characteristics. The laws governing such movement for shallow water waves are not known, and they become further complicated by the unequal duration of the positive and negative velocities, which accordingly cannot be represented by a simple sine function.

In the presence of ripple marks along the bottom, the eddies behind the ripples considerably modify the movement of sand during the passage of the wave troughs. The influence of ripple marks on the mode of sand transportation is complex and not fully understood, but the process is an effective means of sorting the sand sizes along the bottom. In a shallow extended sea with an ample supply of sand this circumstance favors the development of a stable bottom configuration. If the stable configuration is attained, continued sand movement seaward or shoreward ceases. Moreover, the equilibrium condition will be such that waves emerging from a central deeper region and moving toward the shore are damped only gradually and reach the shore area with negligible energy and without the intervention of breakers. The same statement applies to waves generated in the shallower zones, so that in essence no breakers occur anywhere along the shore.

Under a stable bottom configuration the dissipation of wave energy will be brought about in part by viscous forces associated with the laminar boundary layers of the ripple marks, and in part by the destruction of the kinetic energy of the eddies originating in the ripple marks. Where ripple marks are an important element in the mechanism of energy loss, the theoretical evaluation of such loss is difficult. Although the problem is amenable to experimental attack, the desired data are as yet lacking.

In the absence of critical data on the influence of ripple marks in energy loss, the question of dissipation may be approached by supposing that it would involve essentially the same process of boundary dissipation as when the waves are moving over a smooth and firm surface. In this instance no loss due to ripple marks is assumed, and the critical bottom slope required for the absence of wave breaking will be smaller than that required if ripple marks are present.

The problem of the critical bottom slope is approached from the viewpoint that an equilibrium profile is to be developed. This solution will also geometrically define a bottom slope such that a sea encroaching on it will not develop breakers.

In this treatment, the shallow sea is considered as having a trapezoidal cross section, consisting of a central basin bordered by gentle slopes reaching to the shores. The central region is of sufficient depth and of proper fetch for the generation of waves by the prevailing winds. In the sloping area the waves move with the maximum possible heights, but without breaking. The energy dissipation in a given wave will be computed on the basis that the elevated portion of a wave approximates the form of a solitary wave.

For the limiting height of the solitary wave the ratio

$$h_1/H = 3/4 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

may be taken as being characteristic (see Fig. 2).

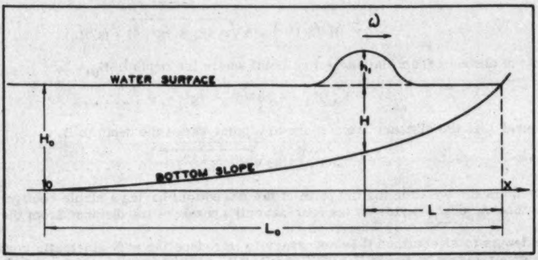

Fig. 2--A solitary wave advancing over a shoaling bottom

One of the authors has investigated the dissipation of energy in a solitary wave, basing the analysis on the boundary layer theory of unsteady motion developed by BOUSSINESQ [1878]. It appears that there is a satisfactory agreement between the theory and the experiments of RUSSELL [1838]. According to this analysis the rate of energy dissipation per unit width of crest may be represented as

$$dE_1/dt = N_1 \rho \nu^{1/2} g^{5/4} h_1^{7/4} \qquad (8)$$

where $N_1 = 0.7719$, ρ is the density of the fluid, ν is the kinematic viscosity of the fluid, g is the acceleration of gravity, and h_1 is the crest height above the undisturbed water level. For waves moving with limiting heights,

$$dE_1/dt = M_1 \rho \nu^{1/2} g^{5/4} H^{7/4} \qquad (9)$$

where $M_1 = 0.4666$, inasmuch as the ratio expressed by (7) is now applicable. The energy of the wave per unit width of crest is given by

$$E_2 = N_2 \rho g H^{3/2} h_1^{3/2} \qquad (10)$$

where $N_2 = 1.540$. Denoting the wave velocity by ω,

$$dE_2/dt = \omega (dE_2/dx \qquad (11)$$

which yields

$$dE_2/dt = (3/2) N_2 \omega \rho g \sqrt{h_1 H}\, [h_1 (dH/dx) + H(dh_1/dx)] \qquad (12)$$

Using (7) and Russell's law of velocities,

$$\omega = \sqrt{[1 + (3/4)]gH} \qquad (13)$$

there results finally

$$dE_2/dt = M_2 \rho g^{3/2} H^{5/2} (dH/dx) \qquad (14)$$

where $M_2 = 3.969$. By the principle of the conservation of energy

$$dE_1/dt + dE_2/dt = 0 \qquad (15)$$

and substituting from (10) and (14) there is obtained

$$d(H^{7/4}) = -A \nu^{1/2} g^{-1/4} dx \qquad (16)$$

where $A = (7/4)(M_1/M_2)$. Equation 16 is the differential equation of water depth. Integrating, and assuming that at $x = 0$ the depth of the water is H_o,

$$H_o^{7/4} - H^{7/4} = A \nu^{1/2} g^{-1/4} x \qquad (17)$$

or

$$1 - (H/H_o)^{7/4} = A \sqrt{\nu / (H_o^{3/2} g^{1/2})} \cdot (x/H_o) \qquad (18)$$

If L_o is the distance from the shore to a point where the depth is H_o,

$$L_o/H_o = 4.86 \sqrt{(H_o^{3/2} g^{1/2} / \nu} \qquad (19)$$

and if in general L is the distance from shore to a point where the depth is H,

$$L/H = 4.86 \sqrt{(H^{3/2} g^{1/2}) / \nu} \qquad (20)$$

Equation 20 is the equation for the form of the sea bottom having a stable configuration. It is readily seen that the depth varies as the four-sevenths power of the distance from the shore.

For the depths to be obtained it is necessary to introduce the eddy kinematic viscosity. Examination of the experiments by Bazin [DARCY and BAZIN, 1865] on solitary waves of channels of moderate size shows that the eddy kinematic viscosity may be four to five times as large as the true viscosity of water.

Using the value $\nu = 0.060$ in cgs units, several values of the distance from shore for selected depths were computed from (20), and are shown in Table 1.

Table 1--Distance from shore for various depths

H	L
m	km
4.0	40.0
3.0	24.0
2.0	12.0
1.0	3.5
0.5	1.0
0.2	0.21
0.1	0.06

According to the values in the table, a solitary wave three meters high in water four meters deep will continue to lose energy at a maximum rate, and after traversing the remaining distance of 40 km to the shore, will reach the shore line with zero height. Nowhere during the motion is a breaker developed. The same statement applies to a train of waves of any normal amplitude moving over the same path.

Geological implications of the theory--The data of Table 1 indicate that the bottom slope decreases with distance from the shore, and mathematically it extends outward for an infinite distance. Theoretically it would be necessary to move several hundred miles from shore to attain moderate depths of a hundred or so feet, but practically it is only necessary to consider the shoreward portion of the curve. If a sea several hundred feet deep shoaled at any convenient bottom slope to a depth of a few score feet, and from there on to the shore had the critical bottom profile required by theory, the wave energy would be dissipated in the manner described. The only restrictions are that the seaward extension of the bottom slope be relatively gradual (that is, not abrupt enough to change the physical nature of the oscillatory waves), and that the critical slope extend far enough from shore to permit control of the dissipation of wave energy. Although no experimental data are available, it is believed that if the waves reach a point about 25 mi from shore without breaking, and there pick up the critical bottom profile, the profile will control the wave behavior thereafter.

These flexible features in the theory are advantageous from a geological point of view in that they permit considerable variation in the offshore sea bottom without essentially affecting the nearshore picture. Figure 3 illustrates a hypothetical case which has been checked with the requirements of theory. The sea is 200 ft deep in the central portion, with the bottom rising at a rate of about 10 ft/mi to a depth of 20 ft, at which depth the critical bottom slope required by theory begins, and extends the remaining 50 mi to the shoreline. In this instance moderately deep water may be reached at distances from shore considerable less than literally required by the mathematical theory.

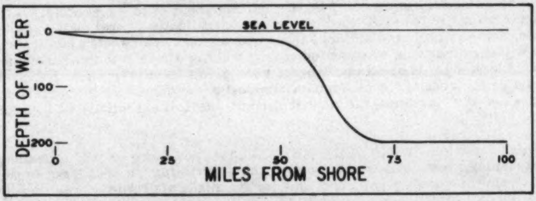

Fig. 3--Hypothetical shallow sea with sloping bottom

The data of Table 1 also indicate that the stable configuration of the bottom slope under conditions of no breakers is such that the slope on the beach is of the order of 1/600; and that it diminishes to a slope of about 1/3500 at a distance about two miles from the shore. Farther out, 15 mi or more from the shore, the bottom slope is about 1/16,000, but the average slope for the first 25 mi from shore is of the order of 1/10,000, or about six inches to the mile. These very gentle bottom slopes are present at equilibrium, which supposes that the sea level has been at a stillstand for a sufficiently long time to attain equilibrium.

Present shore lines have slopes considerably in excess of these values, on the average. Most beaches have slopes in excess of 1/100 or even 1/50, so that adequate wave energy is available for the development of normal shore features. The writers are aware of only one extensive region in which slopes of about the critical value may be present. This is along the east coast of China between the Yangtze and the Shantung Peninsula, where hydrographic charts indicate that water depths of 30 ft are attained some 80 or 90 mi offshore. The slope of the shore is so gentle that the tides move in and out for many miles. The shore itself is said to be a flat expanse of relatively firm sandy silt with no distinguishing features. A number of miles offshore, where the bottom slopes increase to some degree, hydrographic charts indicate shifting sand bars, but whether these are wave-built is not known to the writers.

There are some suggestions of very quiet seas in the geological past. In the Pennsylvanian cyclothems of Illinois and elsewhere, coal deposits are often found overlain by fossiliferous marine shales with knife-edge contacts, indicating that the marine muds were deposited on the unconsolidated organic material with no disturbance of the surface. This deposition would require conditions much as the theory provides: a transgressive sea free of any wave action strong enough to agitate the loose organic matter. Some of the Pennsylvanian coals must have been laid over very extensive areas which were close to sea level over their entire extent. On such a terrain an encroaching sea may encounter slopes of the order required by theory.

MOORE [1929] cites instances of Pennsylvanian limestones which have every appearance of extending practically to the shore lines of the seas which deposited them. There is also a remarkable absence of sea cliffs or other erosive shore features in the cyclothem areas, and Moore concludes that on the whole the seas were relatively shallow and displayed very little if any wave or current action. In addition to the preservation of the upper surfaces of coal beds, fossil organisms are found with very delicate structures well preserved. The associated fauna suggests water a few fathoms in depth, which would be seriously disturbed if strong wave or current action were present.

In many Pennsylvanian areas the relief of the entire depositional surface must have been very small, as Moore points out, so that very slight changes in the relative position of sea level would result in pronounces shifts in the strand line. Such shifts, occurring over very gentle slopes, would probably satisfy the conditions expressed in the theory, in that the advancing edge of the water would be relatively quiet, much as a sheet of water spreading over a floor.

It is not suggested that gentle bottom slopes were the rule in ancient epicontinental seas, inasmuch as there is ample evidence for the work of strong waves and currents in the geological column. The point to be emphasized is that shore agents as they are now experienced may have been essentially inoperative at certain times in areas of low relief and gentle slope, such that old soil horizons, delicate organic structures, and other unresisting features may be preserved even under the conditions of an invading sea.

The theoretical development implies that an initial slope steeper than that demanded by theory could develop into an equilibrium profile by the shifting about of loose materials on the sea bottom, such that in later stages of the still-stand the active operation of typical shore agents may have ceased. Under such equilibrium conditions the epicontinental seas would also drain off the equilibrium profile without displaying wave action during their retreat. It is interesting to speculate whether certain blanket sands or sandy silts, of widespread occurrence and relatively uniform thickness, could be the result of such adjustments during the encroaching stages of the sea, with the result that when the sea retreated, the blanket deposit was left essentially without further disturbance.

The St. Peter sandstone [DAKE, 1921; KELLER, 1945] has long offered a challenge in its genesis inasmuch as it displays both aeolian and aqueous characteristics. It seems not impossible that a broad blanket of sand, formed by transport and sorting associated with ripples during the development of an equilibrium profile, may be modified locally by wind action as the sea retreats. A study of some of the extensive sheets of sand or silty sand in the geological column in terms of equilibrium profiles may yield interesting information on the possible occurrence of critical slopes during marine invasions at various times in the geological past. Other features which may be considered are possible relations between average sand size and water depth in shallow seas. As a general rule average size decreases exponentially in the direction of transport in the absence of tectonic controls, and if the bottom slope is itself a power function, there may be predictable relations between average particle size and water depth which would permit a testing of the hypothesis of equilibrium slopes during deposition.

The question of the role of shore currents in forming typical shoreline features is also pertinent here. Along exposed coasts tidal currents are often strong enough to develop bars and other features, and the repeated mass movements of water in and out with the tides exerts a sorting action on the bottom materials. Whether tides alone could develop deep scour and fill phenomena parallel to exposed shores, or could pile material into broad barrier beaches, is perhaps doubtful. It appears more likely that such major features require the added energy supplied by breaking waves, both in working on the bottom materials and in enhancing the strength of the shore currents.

Summary--This paper is primarily an attempt to demonstrate that physical conditions may be set up which control the dissipation of wave energy in such manner that the waves do not break as they approach a shelving shore. The theoretical development showed that the necessary physical conditions are not impossible in nature. Moreover, the suggestion is strong that at times in the geological past such critical conditions did exist; or that it was possible for them to develop by a shifting of loose materials on the sea bottom. Ancient shore features are usually interpreted from the textures and forms of the sediments left behind, or from associations of inferred environments read from linear sand bodies, lagoonal shales, and the like. In the light of the present development it appears possible that at times the strand line may leave no perceptible mark on the deposits, but that instead they may grade from sediments deposited on broad alluvial plains to sediments deposited in shallow marine water with no line of demarcation separating the two. The wide belt embraced by rising and falling tides would also in such instances make for a complete gradation from one type of depositional environment to the other.

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THE RELATION BETWEEN EARTH MOVEMENTS AND VOLCANISM IN THE SAN JUAN MOUNTAINS OF COLORADO

Esper S. Larsen, Jr.

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Abstract--The late Tertiary volcanism in the San Juan Mountains of southwestern Colorado followed a long interval during which the crust was stable. The volcanic rocks have been divided into four main groups, (1) those of pre-Potosi (?) age in the eastern area, (2) the Lake Fork quartz latite, San Juan tuff, and Silverton volcanic series, (3) the Potosi volcanic series and the Fischer quartz latite, and (4) the Hinsdale formation separated by long intervals without eruptions. Each of the groups is made up of rocks from basalt to rhyolite with chemical and other peculiarities. During the eruption of a group there was little deformation but there was subsidence after the eruption of two of the groups and doming after the eruption of the last group.

The magma moved into the area from the sides and was erupted about as rapidly as it moved in. For the group named the Potosi volcanic series, the first eruptions had a composition near that of the primary magma - dark quartz latites. Their eruption was followed by a short time without eruptions during which the magma became layered by crystal settling. The next eruptions were rhyolites followed abruptly, probably because of active movement of magma, by dark quartz latites. The process was repeated three times.

Subsidence caused by withdrawal of magma followed, and after a long time a new and different magma moved into the area and yielded the rocks of the Hinsdale formation. After the Hinsdale, a magma intruded the area with subsequent doming, but without eruptions.

Introduction--The volcanic and associated rocks considered in this paper cover a large area of southwestern Colorado known as the San Juan region. For a general description of the geology of this region, see CROSS and LARSEN [1935].

Pre-volcanic structure--The Earth history in the western part of the area, as interpreted from the sedimentary beds, is shown in the north-south cross sections across the Needle Mountains in Figure 1. The eastern part of the area is covered by Tertiary volcanic rocks.

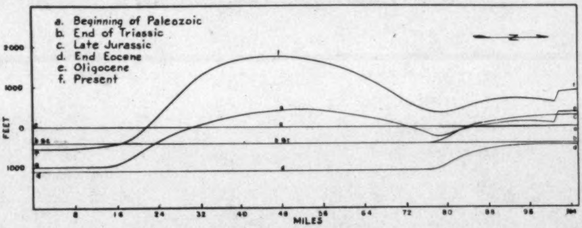


Figure 1--Evolution of a north-south section across the Needle Mountains; base of Paleozoic with respect to sea level

After the deformation at about the end of the Eocene epoch, erosion reduced the area to one of low relief. The Telluride conglomerate was deposited on this surface in the northwestern part of the area, and in the southeastern part of the area, the Blanco Basin formation. There are no volcanic rocks in these formations except near their upper margins, and volcanic rocks overlie them without apparent deformation.

Volcanic history--In the northwestern part of the mountains the first eruptions during the Mioce formed the Lake Fork Volcano. This was followed by a clastic deposit, the San Juan tuff, which is several thousand feet thick over a large area. The deposition of the San Juan was followed by an interval without volcanic eruptions and in places deep canyons were eroded, nearly to the base of the tuff. The Miocene eruptions which followed formed a succession of rhyolites and varied quartz latites named the Silverton volcanic series. Several intervals with canyon erosion separated some of these eruptions.

The deep canyons, cut in the young volcanic pile several times during San Juan and Silverton time, show that the crust must have remained relatively stationary throughout these eruptions and that the volcanic rocks rose above the surrounding surface as a high mountain mass.

The lavas of the Potosi volcanic series followed those of the Silverton and were spread on a surface of moderate relief that was cut by erosion on the Silverton and older rocks. In the area where the Silverton and San Juan rocks are best developed, this surface is several thousand feet higher in elevation than the bottoms of the canyons which were eroded after San Juan and during Silverton time. It follows that the area occupied by the Silverton rocks must have been depressed several thousand feet after the Silverton eruptions. Table 1 shows the succession from oldest to youngest.

Table 1--Succession of volcanic rocks[a] from oldest to youngest

Western part	Eastern part
Lake Fork quartz latite	Quartz latites
San Juan tuff	Erosion
Erosion to canyons	Trachydolerites
Silverton volcanic series	
Picayune quartz latite	
Eureka rhyolite	
Erosion to canyons	
Burns quartz latite	
Erosion to canyons	
Pyroxene quartz latite	
Subsidence and erosion to a mature topography	
Potosi volcanic series	
Conejos andesite (quartz latite[b])	
Erosion to canyons	
Treasure Mountain rhyolite	
Sheep Mountain quartz latite	
Erosion to canyons	
Alboroto quartz latite (rhyolite[b])	
Huerto andesite (quartz latite[b])	
Erosion to canyons	
Piedra rhyolite	
Erosion to canyons	
Fisher quartz latite	
Subsidence and peneplanation	
Hinsdale formation	
Doming	

[a] The formation names used in this table and elsewhere in this paper are those at present accepted by the U. S. Geological Survey. Final chemical and petrographic studies of the formations show that the rock names attached to the formation names are commonly not appropriate. The formations designated as quartz latites are rhyolites or near rhyolites; those designated andesite are quartz latites.

[b] The rock names preferred by the author follow the U. S. Geological Survey names in parentheses.--Ed.

The canyons, eroded four times during the period the lavas of the Potosi series were erupted, are well developed in the central part of the Potosi mass but are missing near the borders of the mass on the north, east, and south. Thus, during Potosi and Fisher time the crust in the central part of the volcanic area remained nearly stationary while the borders must have been depressed.

Following eruption of the Fisher quartz latite of the Miocene the San Juan peneplain was developed. In the cental part of the Potosi and Fisher volcanic mass it is as much as several thousand feet above the bottom of the canyons cut in the older rocks. Therefore, this central area must have been greatly depressed after eruption of the Fisher. The borders of the area remained nearly stationary or may even have been elevated.

The basalt and latite of the Hinsdale formation poured out on the San Juan peneplain in Pliocene (?)

time. In late Pliocene and Quaternary time the whole mountain mass was domed to form the present mountains. Undulations on the dome form the basins of the Gunnison River, Saguache Creek, and the Rio Grande. A contour map of the base of the volcanics with the present structure much generalized is shown in Figure 2.

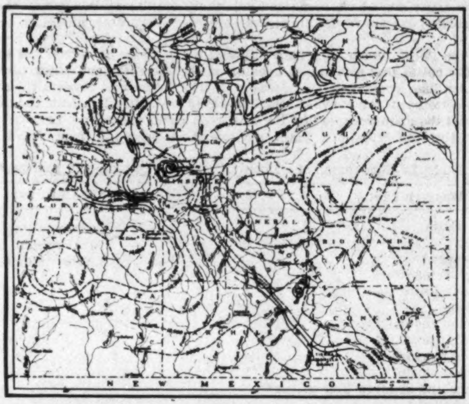
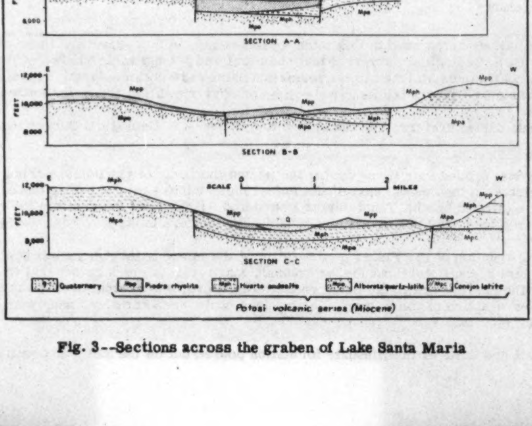

SAGUACHE
DOLORES
MINERAL
RIO GRANDE
CONEJOS
NEW MEXICO

Fig. 2--Contour map of the base of the volcanic rocks

Faulting--Large areas of the volcanic rocks show few faults, but complicated groups of faults are present in some zones. One such zone is in the eastern part of the San Cristobal quadrangle and adjoining areas. It is about 30 mi long and only a few miles wide. In the northern part of this area there is a graben a few miles wide and downdropped more than 1000 ft. In places the bounding faults give place to monoclines with the rocks on the upthrown side dipping into the fault. Locally the rocks within the graben dip away from the fault. Sections across the graben are shown in Figure 3.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MILES
Quaternary
Piedra rhyolite
Huerta andesite
Alboroto quartz-latite
Conejos latite
Potosi volcanic series (Miocene)

Fig. 3--Sections across the graben of Lake Santa Maria

Many of the faults of this area have cross sections like the one shown in Figure 4, the plane of which is normal to the main fault in Williams Creek. Displacement is 2500 ft. The beds on the upthrown side of the fault are nearly horizontal for miles. Those on the downthrown side dip into the the fault and a mile from the fault they again become horizontal and are at approximately the same altitude as on the opposite side of the fault. The deformation simply bent a narrow strip of rock down into the fault.

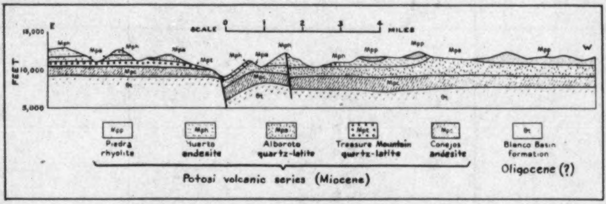

Fig. 4--Section across fault in Williams Creek

The grouping of the volcanic rocks--The Miocene and Pliocene (?) volcanic rocks of the region have been divided into four major groups. The pre-Potosi rocks of the eastern area have been separated from those of the west because the rocks of the two areas, which were nowhere seen in contact, are very different petrographically. Otherwise, these divisions are made because the eruptions of the groups were separated from each other by long intervals without eruptions but with erosion that resulted in a mature topography or a peneplain. Moreover, between the eruptions of the Silverton and Potosi volcanic series and between those of the Fisher quartz latite and the Hinsdale formation there were periods of great depression and deformation. The intervals of erosion within the groups were relatively short and only canyons were formed. No extensive deformation was found within the groups.

The rocks of each of the groups range from basalts to rhyolites. Those of any of the groups belong to a relatively simple petrographic province and their plotted analyses fall near smooth variation curves. The variation curves of the four groups are different. The Potosi and Hinsdale show this variation better than the others (see Fig. 5).

Conclusions--To explain the observed facts the following hypothesis is proposed: Although the eruptions of the larger groups formed domes some of which were nearly a hundred miles across and over a mile high, there was little movement of the crust immediately before and during the eruptions and the new volcanic accumulation stood as a dome above the general level. The magma is believed to have moved into the area from the sides and was erupted about as rapidly as it moved in. The intervals of erosion represent times during which no magma moved in. The subsidence after the eruption of the lavas of the Silverton series and again after those of the Fisher quartz latite were caused by withdrawal of magma from the chamber. After a long interval a new magma differing chemically from the older magma was introduced into the area and formed the next volcanic series. The final doming after the Hinsdale was caused by the injection of magma without much eruption.

The following hypothesis is proposed to explain the succession of events during the eruption of a group, such as the Potosi volcanic series: Magma relatively low in silica was forced into the area and was erupted at the beginning of Potosi time. It formed the dark Conejos andesite (quartz latite). The small bodies of rhyolite in the Conejos represent pockets of local differentiation. Movement of magma ceased until the Treasure Mountain quartz-latite (rhyolite) was erupted. Between the Conejos and Treasure Mountain eruptions the magma differentiated by crystal settling to the stage where the upper part was rhyolite. Hence the Treasure Mountain rocks are rhyolitic. The local bodies of dark rocks in the Treasure Mountain represent deeper magma that broke through the rhyolite. Finally, probably with an increased activity to account for the sharp break between the dark and light members, the magma erupted was the dark Sheep Mountain quartz latite. During Sheep Mountain time local pockets of rhyolitic magma furnished the small bodies of rhyolite in this unit.

An interval without eruption allowed canyon erosion and the process was repeated for the Alboroto and Huerto and again to form the Peidra rhyolite.

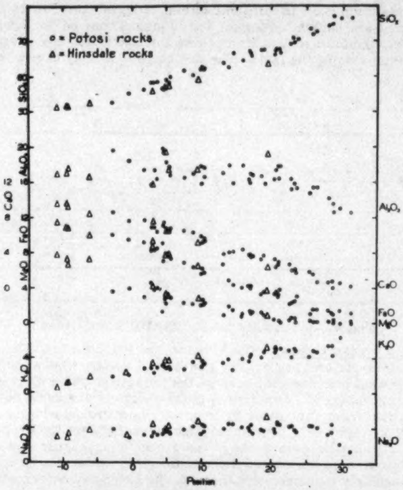

Fig. 5--Variation diagram of the Potosi volcanic series and Hinsdale formation of rocks; position is 1/3 SiO_2 / K_2O - FeO - MgO - CaO.

After the Potosi and Fisher eruptions, magma was withdrawn and the crust subsided. No eruptions took place for a long time, and then a new and different parent magma moved into the area and furnished the Hinsdale rocks.

Finally the intrusion of a large body of magma domed the area.

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RADIOACTIVITY MEASUREMENTS IN THE KIRKLAND LAKE AREA, NORTHERN ONTARIO

Howard A. Slack

Abstract--The measurement of the radioactivity of 136 rock samples within and around the Round Lake batholith near Kirkland Lake, Ontario, shows a regular increase in radioactivity from south to north. This is believed to be due to the northward plunge of the batholith and the migration of radioactive elements towards the top surface. This agrees with previous work by Keevil and Ingham on other batholiths.

This evidence of the rise of radioactive elements suggests that the radioactivity of the crust as a whole may be much less than that determined from samples taken on its surface. Using values for the lower part of the batholith as representative of the granitic layer it is estimated that at Kirkland Lake 40 per cent of the total heat flow from the interior of the Earth may be accounted for by the radioactivity of the rocks in the top 36 km of the crust.

It is also assumed that erosion has removed the more highly radioactive material from the Earth's surface and deposited it as sedimentary, heat-producing shelves or dumps along the edges of the continents. These dumps may have determined the location and their heat may have assisted in the formation of marginal mountain ranges.

General statement--A precise method of measuring radioactivity is to count individual disintegrations of nuclei of radioactive atoms. In weakly radioactive materials such as ordinary rocks, this may be done by counting the emission of alpha particles. Since nearly 90 per cent of the heat energy from radioactive disintegration in rocks is due to alpha ray emission, alpha counts afford a direct means of determining the rate at which radiogenic heat is being produced from the uranium and the thorium series in any rock [KEEVIL and GRASHAM, 1943], [KEEVIL, KEEVIL, INGHAM, and CROMBIE, 1943]. After allowance has been made for the heat produced by radioactive potassium the rate of production of radiogenic heat is given [KEEVIL, 1943] by the equation

$$H = 2.25a \text{ cal/gm/m.y.}$$

where a = radioactivity in α/mg/hr

Nearly all rocks so far examined contain a few parts per million of uranium and thorium. If the quantities of these elements present be determined by counting their rate of emitting alpha particles then the rate at which they generate heat can be calculated.

In this paper the results of such measurements on a suite of rocks from Kirkland Lake area are given and correlated with the local geology. The calculated heat generated by the radioactivity of these near surface rocks is discussed in relation to the known heat flow in nearby mines and the formation of magmas, ore solutions, and folding.

Geology of the area--The oldest rocks in the area are of Keewatin age. They consist chiefly of acidic and basic lavas, tuffs and sediments with occasional bands of iron formation. The Keewatin also includes bodies of diorite and gabbro in certain parts of the area.

A prominent belt of Timiskaming rocks extends through the Kirkland Lake and Larder Lake areas, eastward into Quebec. Another belt crops out a few miles to the south of Larder Lake. The Timiskaming rocks, which consist of conglomerate, greywacke, quartzite and slate, are believed to form tightly-folded synclines.

Both Keewatin and Timiskaming rocks were intruded in the Algoman by the large Round Lake batholith which is composed of granite in the southern and central regions and syenite in the northern section. The intrusion of this batholith was followed by gold mineralization. The principal deposits are in rocks of Keewatin and Timiskaming age.

Flat-lying sedimentary rocks of Cobalt age, consisting of conglomerate, greywacke, and slate, are found east and south of the batholith. Sill-like bodies of Keweenawan diabase and gabbro have been intruded into the Cobalt rocks and also appear as dikes cutting the Algoman granites and older formations although none have been found within the batholith.

Much of the bedrock surface is concealed by deposits of glacial origin consisting of boulder clay, stratified clay, sand, and gravel. Sand deposits are particularly widespread over the western part of the Round Lake batholith, which was not included in this study.

The northern edge of the Round Lake batholith is about five miles south of Kirkland Lake, Ontario. It extends for about 20 mi in a north-south direction, and rather more from east to west.

Measurements of radioactivity in the Kirkland Lake area--The activities of 136 specimens collected during the summer of 1947 by L. S. Collett were determined by counting the rate of emission of alpha particles from known weights of the powdered specimens by a method already described [KEEVIL and GRASHAM, 1943]. The average activities for rocks of different types and from various locations within and outside the batholith are summarized in Table 1. The individual activities of 120 specimens are plotted on Figure 1. The remaining 16 specimens were collected along the road extending north north-west from Swastika outside of the map area.

Discussion of results--An examination of Figure 1 shows that the activities are decidedly irregular in any one area. Without doubt this is due to the fact that only hand specimens were used for analysis. These could not be truly representative, and they contain different quantities of such accessory minerals as allanite, zircon, and sphene, which have been found to be highly radioactive,

Table 1--*Radioactivity measurements in the Kirkland Lake area*

Rock age	Location	Rock types	Number of specimens	Average activity	Probable error	Average heat production
				α/mg/hr		cal/gm/m.y.
Keweenawan		Diabase and gabbro	4	0.31	± 0.04	0.70
Cobalt		Conglomerate and greywacke	3	0.78	0.03	1.75
		Slate	3	1.44	0.21	3.25
Algoman	Within batholith north of Round L.	Syenite	7	1.45	0.40	3.26
	west of Round L.	Syenite-granite gneiss	16	0.70	0.23	1.57
	northern rim east of Round Lake	Granite gneiss	4	0.83	0.43	1.86
	eastern rim	Granite gneiss	4	0.40	0.07	0.90
	southern rim	Granite gneiss	3	0.07	0.03	0.16
	central portion	Granite gneiss	36	0.26	0.07	0.58
	Outside batholith	Granite	4	0.91	0.25	2.04
Timiskaming	Northwest edge of belt and portion east of Larder L.	Greywacke and quartzite	8	0.40	0.20	0.90
	Main belt	Altered sediments, quartzite, conglomerate, and slate	8	2.52	1.20	5.70
Keewatin	In batholith	Amphibolite	2	1.00	0.40	2.25
	Outside batholith	Sediments, andesite, basalt, diorite, and gabbro	33	0.18	0.10	0.40

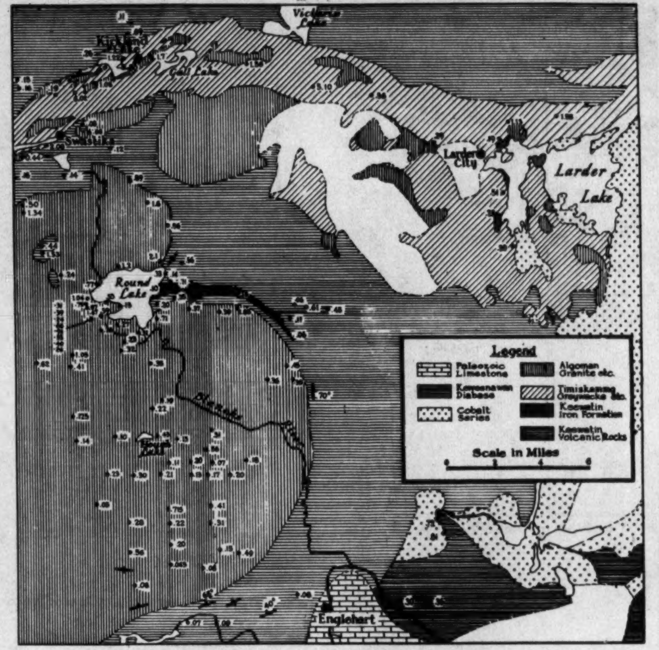
Victoria Lake
Kirkland Lake
Gull Lake
Swastika
Round Lake
Larder City
Larder Lake
Blanche
Englehart
Legend
Paleozoic Limestone
Algoman Granite etc.
Keweenawan Diabase
Timiskaming Greywacke etc.
Cobalt Series
Keewatin Iron Formation
Keewatin Volcanic Rocks
Scale in Miles
0
2
4
6

Fig. 1--Location of specimens from the Round Lake batholith (Algoman granite) and vicinity, for which the radioactivity has been measured; the radioactivity is expressed in alpha particles emitted per milligram of rock per hour (α/mg/hr).

although present only in small quantities in rocks. Determinations of the radioactivity of several samples from the same outcrop have shown the possibility of variations in activity between such samples as shown in investigations by KEEVIL, KEEVIL, INGHAM and CROMBIE [1943]. In this work, however, a sufficient number of specimens was collected so that only the average values for each group of rocks are used in the discussion. The probable error for each group has been calculated and given in Table 1. These are sufficiently small so that it is considered that the conclusions drawn from the data are valid.

It will be observed from Table 1 that the oldest rocks in this area, the Keewatin series, have a relatively low average activity of 0.18 α/mg/hr (average of 33 samples). The main belt of the Timiskaming rocks has a relatively high average activity of 2.52 (eight samples). This belt extends through the Kirkland Lake and Larder Lake areas. The belt which outcrops a few miles to the south of Larder Lake has a much lower average activity of 0.40 (eight samples). The Kirkland Lake-Larder Lake "break" or fault and the mineralization along it may account for the increased radioactivity of the northern belt. Previous to this project 13 specimens were collected between Kirkland Lake and Larder Lake and their average activity given as 1.57 (unpublished data from Keevil). Considering the high degree of localization of radioactivity in this belt, the agreement is good. The slate of the Cobalt series has a higher average activity (1.44, three samples) than the conglomerate and greywacke (0.78, three samples). The Keweenawan diabase dikes and gabbro sills have a low average activity of 0.31 (four samples).

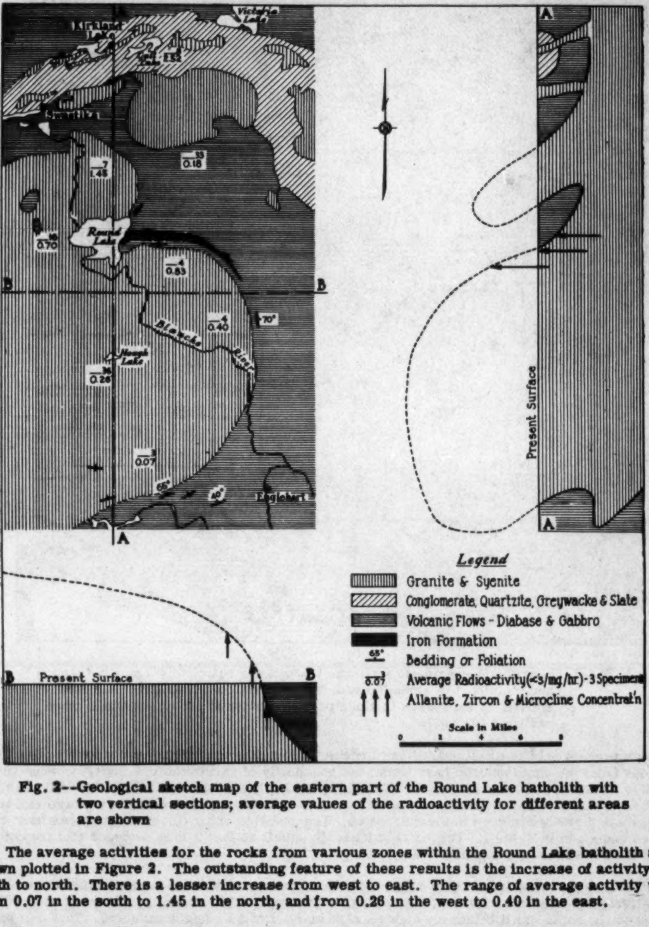
Kirkland Lake
Victoria Lake
Round Lake
Blanche River
Hough Lake
Englehart
7 / 1.45
33 / 0.18
16 / 0.70
4 / 0.83
4 / 0.40
36 / 0.26
3 / 0.07
70°
65°
40°
A
B
Present Surface
Legend
Granite & Syenite
Conglomerate, Quartzite, Greywacke & Slate
Volcanic Flows - Diabase & Gabbro
Iron Formation
Bedding or Foliation
Average Radioactivity(α's/mg/hr.)-3 Specimens
Allanite, Zircon & Microcline Concentrat'n
Scale in Miles
0 2 4 6 8

Fig. 2--Geological sketch map of the eastern part of the Round Lake batholith with two vertical sections; average values of the radioactivity for different areas are shown

The average activities for the rocks from various zones within the Round Lake batholith are shown plotted in Figure 2. The outstanding feature of these results is the increase of activity from south to north. There is a lesser increase from west to east. The range of average activity varies from 0.07 in the south to 1.45 in the north, and from 0.26 in the west to 0.40 in the east.

There is some field evidence from dips of the foliation and in the surrounding rocks that the Round Lake batholith plunges northward. If this is the case, as many geologists believe, then the structure is as illustrated diagramatically in Figure 2 and the top of the batholith is more radioactive than the lower portions.

It is suspected that this may be due to the increase of accessory radioactive minerals although the allanite, sphene, and zircon content of these rocks has not been studied petrographically. W. W. Moorhouse of the Geology Department, University of Toronto, reports a general increase in microcline and decrease in quartz from south to north in the Round Lake batholith. The rocks in the northern part of the batholith are syenite rather than granite, but no contact between the two types has been found. The transition may be gradational. This postulated rise of radioactive elements during the formation of the batholith is similar to that which JEFFREYS [1929, pp. 159-160] has suggested to take place in the Earth's crust as a whole.

Comparison of four batholiths--A systematic study of the radioactivity of the Bourlamaque, Cheddar, and Elzevir batholiths has already been undertaken by N. B. Keevil, W. H. Ingham and their associates at the University of Toronto. The Bourlamaque batholith in Abitibi County, northwestern Quebec, 60 mi east of Noranda is assigned to the Algoman [KEEVIL, KEEVIL, INGHAM and CROMBIE, 1943; INGHAM, 1943; and GUSSOW, 1937]. The Elzevir batholith in southeastern Ontario, 40 mi north of Belleville is generally considered post-Grenville and post-Hastings in age [INGHAM, 1943; ADAMS and BARLOW, 1910]. The Cheddar batholith, considered to be one of the same age, is at Cheddar, Ontario, about three miles south of Wilberforce [BARNES, 1944].

The average activities for the rocks from various zones within these four batholiths are shown in Figure 3. The most striking feature common to these four batholiths is the high average value of radioactivity near the rims and the lower values toward the centers. This can, as previously discussed, be attributed to the migration of the radioactive elements to the top surface of the batholiths and the subsequent effect of erosion. The fact that the ratio of high values to low varies for the different batholiths can be accounted for if we assume that the amounts of the accessory radioactive minerals change from place to place on the Earth's surface. It is interesting to note that the Bourlamaque and Round Lake batholiths of Algoman age are north of a large fault zone considered to extend from Georgian Bay south of Sudbury to Lake Mistassini [NORMAN, 1946; and COOKE, 1946] while the Elzevir and Cheddar batholiths are south of this fault in the Grenville series, and are part of the roots of what is now believed to be a much younger mountain range [GILL, 1948]. The radioactivity of the latter two batholiths of Laurentian age is noticeably higher than that of the Algoman intrusives. This may be due to a greater concentration of accessory radioactive

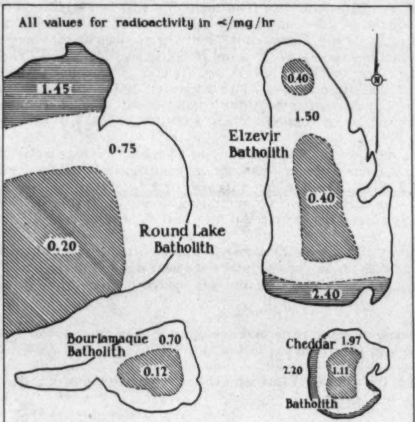

Fig. 3--Sketch showing the general distribution of radioactivity in four Precambrian batholiths in eastern Ontario and western Quebec. All are drawn to the same scale and the values shown are the regional averages of many scores of individual determinations minerals, for the Cheddar batholith is only a few miles south of Wilberforce where numerous pegmatites containing radioactive minerals occur. It was found that the area surrounding the ore deposits at Great Bear Lake was very radioactive [SENFTLE and KEEVIL, 1947] so that it is possible that the area near Wilberforce is also highly radioactive. The Cheddar batholith shows the highest values of the four batholiths now studied. It is the smallest and perhaps the least deeply eroded.

Measurements of heat flow at Kirkland Lake, Ontario--During the summer of 1947, A. D. Misener of the Department of Physics, University of Toronto and two assistants were engaged in measuring the temperature of rocks at various levels in the Lake Shore Mine and the Wright Hargreaves Mine, both situated at Kirkland Lake, Ontario. Rock specimens were taken by them at each point at which a temperature reading was taken and the thermal conductivity measured later [MISENER, 1948]. The specimens were taken at depths ranging from 800 to 6825 ft in Timiskaming sediments and minor acid intrusive bodies.

These rock specimens were made available to the writer and their radioactivity measured to see if there was any variation in the rate of emission of alpha particles with depth.

The alpha activity and the corresponding radiogenic heat for the 19 samples yields an average value of 1.64 ± 0.2 α/mg/hr and 3.69 cal/gm/m.y. respectively. It will be noted that this value is lower than the surface value of 2.52 for the Timiskaming belt of sediments. It was impossible to detect any other appreciable variation with depth.

Radioactivity and heat flow in the crust at Kirkland Lake--It is believed by seismologists that the continents are made up of three layers which are generally considered to be composed of sedimentary rocks and granitic rocks underlain probably by basaltic rocks. The thickness of the uppermost layer, the sediments, is of course irregular but average values of the thickness of the other two have been calculated [HODGSON, 1947]. Between Ottawa and Kirkland Lake, the average value for the thickness of the granitic layer is 17 km and its density is 2.67 gm/cm^3. Recent gravity observations [GARLAND, 1948] seem to indicate a thickening of the granitic layer under Kirkland Lake but for the purpose of the following treatment this will be neglected and granitic rocks will be assumed to make up the 12 km immediately below the five km of Timiskaming sediments. This is assuming that the rocks of the Timiskaming belt are as deep as they are wide (that is, five km). The density of these sediments is 2.67 gm/cm^3 [MISENER, 1948]. The basaltic rocks underlying the granitic layer are 19 km thick and have a density of 2.90 gm/cm^3 [HODGSON, 1947]. The evidence for this layer of basaltic composition is suggested by the very widespread occurrence of basalt and diabase intrusives cutting the older rocks. It will be assumed that these dikes are representative of the basaltic layer [KENNEDY and ANDERSON, 1938].

The sedimentary rocks of the Timiskaming belt have an average activity of 1.64 α/mg/hr and thus the heat emanating from a column one square centimeter in cross section and five km in length will be $1.64 \times 2.25 \times 2.67 \times 5 \times 10^5$ cal/m.y. or 1.58×10^{-7} cal/sec. Since the radioactivity of this belt is higher than that of the surrounding rocks and since this belt is limited in extent, this figure will be slightly reduced because of the lateral flow of heat.

The average activity of the granitic layer is assumed to be equal to that of the low central region of the batholith or 0.26 α/mg/hr and hence the heat due to internal radioactivity emanating from a column of such granite 12 km high and one square centimeter in cross section is 0.61×10^{-7} cal/sec.

The four specimens collected from diabase dikes in this area yields an average activity of 0.31 α/mg/hr and thus the heat produced due to the basaltic layer is 1.24×10^{-7} cal/sec/cm^2.

Summing these up, the total heat flow emanating from the top 36 km due to radioactivity of the rocks becomes 3.43×10^{-7} cal/sec/cm^2.

The total heat flow across the surface of the ground is $K(dt/dx = 7.23 \times 10^{-7}$ cal/sec/cm^2 where K = conductivity of the rock = 0.00640 cal/cm^2/sec and dt/dx = thermal gradient for Kirkland Lake = 11.3° C/km [MISENER, 1948].

Therefore, on the basis of the assumptions made, 40 per cent of the total heat flow from the interior of the Earth may be accounted for by the radioactivity of the rocks in the top 36 km, provided that the assumptions are tenable.

Conclusions--It has been concluded from observations on samples from four batholiths that the radioactivity is highest around the edges and decreases toward the center [KEEVIL, KEEVIL, INGHAM and CROMBIE, 1943]. This has been interpreted as a migration of the accessory radioactive minerals to the top of the batholiths during their formation. The batholiths were subsequently eroded, exposing areas of low radioactivity in the central portions.

The average values of radioactivity of the acid rocks measured in this area are considerably less than those given in the Handbook of Physical Constants [EVANS, GOODMAN and KEEVIL, 1942]. For example, the 74 samples of Algoman syenite and granite, shown in Figure 1, have an average rate of heat production of 1.48 cal/gm/m.y. compared with a world-wide average value for acidic rocks of 5.6 cal/gm/m.y. These lower values are in keeping with the observation that Precambriam granites are less radioactive than later granites [DALY, 1933]. It is possible that the world-wide averages may be lowered when more Precambrian values are included, since up to this time more work has been done on the rocks younger than the Precambrian.

It has already been suggested in this paper that the high radioactivity noted around the margins of batholiths may be due to the rise of radioactive elements during their emplacement. If this is so the deeper parts of the crust may contain less radioactive elements. Thus average values obtained from surface measurements may be too high to represent the average radioactivity of the crust. Both these possible reductions in the radioactivity of the crust strengthen the possibility that the Earth's interior may be cooling and contracting [JEFFREYS, 1929; and BULLARD, 1945] although others have doubted this [SLICHTER, 1941; HOLMES, 1946; and VENING MEINESZ, 1947].

The more highly radioactive parts have been eroded, to be partly dissolved in sea water and chiefly deposited as sedimentary rocks. Relative to the reduced value assumed for the crust, these sedimentary rocks have higher values of radioactivity. For example, in this area the Cobalt and Timiskaming rocks have higher average values than the parts of the batholith now exposed.

If sedimentary material has been carried to the edge of continents and laid down in continental shelves [UMBGROVE, 1947], it is possible that the relatively greater heat produced within the sediments is an added reason for weakness along the edges of the continents and therefore assists in the formation of marginal mountain ranges [SONDER, 1947].

According to the analysis carried out in this project, about 40 per cent of the total heat flow from the interior of the Earth may be accounted for by the radioactivity of the rocks in the top layers. The remaining 60 per cent must then be produced from the deep interior either by radioactivity or by cooling of the core. It must be remembered, however, that in this analysis great assumptions have been made about the distribution of radioactivity in the granitic layer.

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RESISTANCE TO FLOW IN SMOOTH CHANNELS

Ralph W. Powell

Abstract--The distinction is drawn between smooth and rough channel flow, and formulas developed giving Chezy's constant for smooth channels in terms of the Reynolds number, for non-turbulent and ultra-rapid flow.

Introduction--Since the work of NIKURADSE [1932 and 1933] on flow in pipes, the distinction between smooth and rough pipe flow has become well established. But the difference between smooth channel flow and rough channel flow is not as well known. Physically a channel may be said to be hydraulically smooth when the surface roughnesses of the bottom and sides are small enough to be so imbedded in the boundary layer (or rather the laminar sub-layer) that they have no appreciable effect on the flow. In the early days of hydraulic models, it was often found that the flow was too small to give dynamic similarity with the prototype. The surface was then made smoother to increase the flow. But often it was found that this smoothing did no good. The explanation is that at this low Reynolds number the laminar sub-layer was thick enough to bury the roughness, so that the channel was already hydraulically smooth and no additional smoothing could increase the flow.

The first satisfactory discussion of this matter known to the writer was that of KEULEGAN [1938] who proposed a formula for smooth channel flow which in our notation may be written

$$V/V_f = a_s - b + b \log_e (RV_f/\nu) + b\beta_\kappa - \bar{\epsilon} V/V_f \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where V is the mean velocity in the cross-section, V_f is the friction velocity = $\sqrt{\tau_o/\rho} = \sqrt{RSg} = \sqrt{g}V/C$, C is the Chezy coefficient, R is the hydraulic radius, ν is the kinematic viscosity of the liquid flowing; a_s and b are constants discussed below, and $\bar{\epsilon}$ and β_κ are functions of the shape of the cross-section, also discussed below.

Substituting $V_f = \sqrt{g}\, V/C$ in (1)

$$C(1 + \bar{\epsilon})/\sqrt{g} = a_s - b + b \log_e (\sqrt{g}/4) + b \log_e (4RV/\nu C) + b\beta_\kappa$$

If we define the Reynolds number as $\underline{R} = 4RV/\nu$, this becomes

$$C(1 + \bar{\epsilon}) = \sqrt{g} \left\{ a_s - b + b \log_e (\sqrt{g}/4) + b \log_e (\underline{R}/C) + b\beta_\kappa \right\}$$

Letting $\sqrt{g} \left\{ a_s - b + b \log_e (\sqrt{g}/4) \right\} = J$ and $2.3026\, b\sqrt{g} = m$

$$C(1 + \bar{\epsilon}) = J + m \log_{10} (\underline{R}/C) + \sqrt{g}\, b\beta_\kappa \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Keulegan's b is the reciprical of von Kármán's universal constant [BAKHMETEFF, 1936, p. 66], which is generally taken as 0.40, so that b = 2.5. Using this value, (2) reduces to

$$C(1 + \bar{\epsilon}) = 32.65 \log_{10} (\underline{R}/C) + 14.18\beta_\kappa + J \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

β_κ is defined by KEULEGAN [1938], who shows that for a rectangle of breadth B and depth y, $\beta_\kappa = \log_e (1 + 2y/B) - y/B$

Experimental data--In a series of measurements taken by the author in connection with another study, values of C, y, and $\underline{R}$ for a smooth channel of known B were tabulated [POWELL, 1946, Table 1 (a)]. As pointed out elsewhere [POWELL, 1948], this part of the table should have been headed "Tranquil and Shooting Flow," and Table 1 (b) headed "Ultra-rapid Flow."

When the values of $32.65 \log_{10} (\underline{R}/C) + 14.18\beta_\kappa$ are plotted against C (see Fig. 1), it is found that the points lie fairly well on a straight line, and that the line can be taken as passing through the origin. Therefore J in (3) may be taken as zero. (This requires that $a_s = 1.63$.) The equation of the straight line is

$$32.65 \log_{10} (\underline{R}/C) + 14.18\beta_\kappa = 0.792\ C \ldots\ldots (4)$$

which from (3) gives $(1 + \bar{\epsilon}) = 0.792$ and $\bar{\epsilon} = -0.208$. Substituting these values in (2) and simplifying

$$C = 41.2 \log_{10} (\underline{R}/C) + 17.9\beta_\kappa \ldots\ldots (5)$$

Representing the shape correction $17.9\beta_\kappa$ by c_s,

$$C - c_s = 41.2 \log_{10} (\underline{R}/C) \ldots\ldots (6)$$

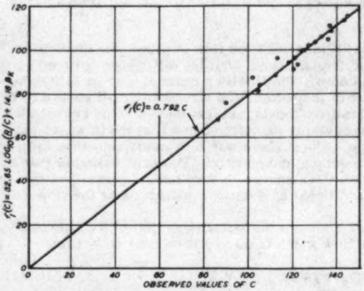

Fig. 1--Relationship between observed Chezy C and f_1(C)

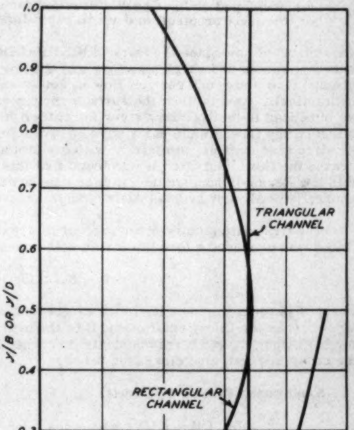

Fig. 2--Values of shape correction c_s

It should be noted that this value of c_s is somewhat different than that used before the 1946 paper. Using the values of β_κ given by KEULEGAN [1938], Figure 2 has been constructed showing values of c_s for various depths in rectangular, triangular, and semi-circular channels.

Constant versus variable $\bar{\epsilon}$--The writer believes that (6) is an improvement on the somewhat similar (11) of his 1946 paper. It reduces the average discrepancy from observed C to 1.98, but the more important advantages are its simpler form and its better theoretical foundation. The $\bar{\epsilon}$ term was originally introduced to take care, in the words of Keulegan, of "the deviations in the velocities imposed by the free surface of the water and by the angles between the walls and the bottom of the channel." Later he came to the conclusion that the effect of the free surface is very small, and that the non-uniform distribution of wall shear produced by the corners in the cross-section is the principal cause of the discrepancy which necessitates an term. It is probably connected with the phenomenon of double spiral flow. In the closing discussion of his 1946 paper, the writer extended Keulegan's work to derive a relationship between $\bar{\epsilon}/(a_o - 1)$ and y/B, where y is the depth and a_o is the ratio of the wall shear at the lower corners of the rectangular section to the mean shear along the whole wetted perimeter. The method applied to values of $y/B \ngtr 0.5$. With the same assumptions as before except that the side-wall shear is assumed to remain constant for values of y/B greater than 0.5, the values are now computed to y/B = 1.0 and are plotted in Figure 3.

Since $\bar{\epsilon}$ depends upon the ratio of depth to width, it would certainly seem that a more accurate formula than (6) would take this into account. This was investigated as follows. Using (3) with J = 0, $\bar{\epsilon}$ was computed for the same data as was used for Figure 1, and from Figure 3, a_o was deter-

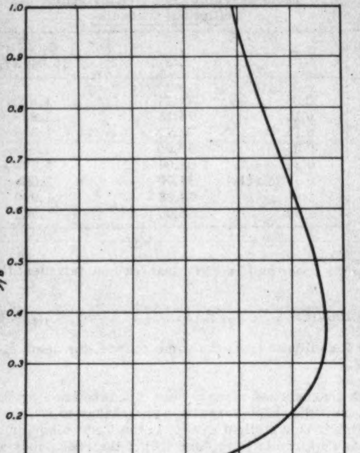

Fig. 3--Relation of $\bar{\epsilon}/(a_0 - 1)$ to y/B

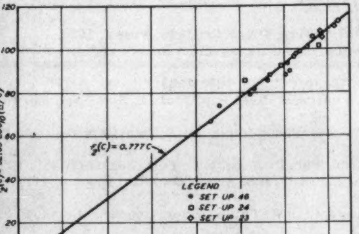

Fig. 4--Relationship between observed Chezy C and $f_2(C)$

mined for each run. The median value was found to be 0.219. It is obvious that the probable error of a value found in this indirect way will be fairly large (the quartile values were 0.140 and 0.252), but for want of a better value it was assumed that a_0 was 0.219 for each run, and from that value and Figure 3 a value of $\bar{\epsilon}$ was computed for each run. These ran from -0.137 for Run 46-1 to -0.221 for Runs 46-5 and 23-4. With these values of $\bar{\epsilon}$ and a table of values of C + 32.65 $\log_{10}$C, C was computed for each run from (3) with J = 0. The average discrepancy from the observed C was now found to be 2.41, which is more than that found when a constant value of $\bar{\epsilon}$ was used. That it is more is probably accidental, but that it would not be much less is probably accounted for by the approximations on which Figure 3 is founded, and by the fact that none of the depths was very small or very large compared with the width, so that $\bar{\epsilon}$ was approximately constant for all runs. It seems best therefore, at least in the present stage of our knowledge of the subject, to use a constant value of $\bar{\epsilon} = -0.208$.

For a channel of infinite width it would seem that $\bar{\epsilon} = 0$ and $C = 32.65 \log_{10}(\underline{R}/C) + J$. In this case J would quite certainly not be zero. (In his 1946 paper the writer found J about 22.0 for this case.) For actual channels of shallow depth, it would seem that the coefficient by which $\log_{10}(\underline{R}/C)$ should be multiplied would lie between 32.65 and 41.2, and J between 22.0 and zero, but the additional accuracy to be obtained by using a variable $\bar{\epsilon}$ and J would seem to be slight.

Effect of neglecting shape correction--Let us next investigate the effect of neglecting the c_s term. In Figure 4 values of $32.65 \log_{10}(\underline{R}/C)$ are plotted against C, and it is found that the values lie fairly well on the line $32.65 \log_{10}(\underline{R}/C) = 0.777\,C$. This is equivalent to (3) with the $\bar{\epsilon}$ and J terms omitted and $\bar{\epsilon} = -0.223$. It reduces to

$$C = 42.0 \log_{10}(\underline{R}/C) \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (7)$$

With the aid of a table of values of C + 42 $\log_{10}$C, values of C were computed by the formula from the same data as used above, and it was found that the average discrepancy from the observed C's was 2.14. This is slightly more than the 1.98 given by (6), but it is open to question whether the increased accuracy of (6) is enough to warrant making the shape correction. If further tests indicate that there is no more difference than shown by this sample, many will certainly prefer to use (7).

Non-turbulent flow--For a semi-circular channel, or a circular pipe flowing half full, if $\underline{R}$ is not more than 2000, the flow will be non-turbulent, and Fanning's f will be $64/\underline{R}$ and

$$C = 2.005\sqrt{\underline{R}} \; . \; (8)$$

If we assume that the flow in a rectangular channel is just half the flow in a rectangular pipe twice as high flowing full, and if we use the values for rectangular pipe computed by DAVIES and WHITE [1929] by the method of BOUSSINESQ [1868], we find that the values of the coefficient of $\sqrt{\underline{R}}$ for rectangular channels are as shown in Table 1.

Table 1--Values of $C/\sqrt{\underline{R}}$ for rectangular channels

y/B	$f\underline{R}$	$C/\sqrt{\underline{R}} = 16.04/\sqrt{f\underline{R}}$
0.000	96.00	1.637
0.050	84.96	1.740
0.100	76.16	1.838
0.125	72.80	1.880
0.167	68.80	1.934
0.250	62.08	2.036
0.500	56.96	2.125
1.000	62.08	2.036
1.500	68.80	1.934
2.000	72.80	1.880

Table 2--Values of $C/\sqrt{\underline{R}}$ for semi-elliptical channels

y/B	$f\underline{R}$	$C/\sqrt{\underline{R}} = 16.04/\sqrt{f\underline{R}}$
0.05	78.24	1.813
0.10	76.16	1.838
0.15	73.12	1.876
0.25	68.00	1.945
0.35	64.96	1.990
0.50 (circle)	64.00	2.005
2.86	64.96	1.990
4.00	68.00	1.945

Turning a square pipe through 45° and using the lower half, we find that for non-turbulent flow in a triangular channel with 1:1 side slopes,

$$C = 2.125\sqrt{\underline{R}} \qquad (9)$$

Making similar assumptions, and using data for ellipses from the same source, for semi-elliptical channels, we obtain the values in Table 2.

Ultra-rapid flow--Ultra-rapid flow in smooth channels has already been discussed in a previous paper [POWELL, 1948] on the basis of (6). If we omit the shape correction and change to (7), the β of that paper is changed to $1/(0.0274\ C + 0.5)$. This makes a slight change in the Vedernikov criterion for each run. These new values were computed and a formula to replace (14) of the 1948 paper was derived, thus

$$C = 42 \log_{10} (\underline{R}/C) + 25.5\,\underline{F} - 10.0\,\underline{V} - 85.0 \qquad (10)$$

The mean discrepancy of the values of C as computed by this formula, from the observed values was found to be 2.41. This is not as good as the 2.15 found for the (14) mentioned above, but the difference is not enough to be very significant.

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ANNUAL FLOODS AND THE PARTIAL-DURATION FLOOD SERIES

W. B. Langbein

Abstract--Flood data are ordinarily listed either in annual-flood series or in a partial-duration series. If the expectancy of a flood in the duration series ϵ is known, then the probability of that flood being an annual flood is shown to be $e^{-\epsilon}$. From this relationship it is possible to transform recurrence intervals in the partial duration series to those in the annual-flood series. It is shown that for equivalent floods, the recurrence intervals in the partial-duration series are smaller than in the annual-flood series, but that the difference becomes inconsequential for floods greater than about five-year recurrence interval.

There are in common use two methods of treating flood data for the study of their frequency of recurrence. The first is the annual-flood array and the second is the partial-duration series. Although most analysts take a tolerant view, some are active protagonists for one method as against the other. The differences can be shown to be largely a matter of definition.

Annual floods--An annual flood is defined as the highest peak discharge in a water year. Only the greatest flood in each year is used. An objection most frequently encountered with respect to the use of annual floods is that it uses only one flood in each year. Infrequently, the second highest flood in a given year, which the above rule omits, may outrank many annual floods.

Partial-duration series ("floods above a base")--The objection noted under annual floods is met by listing all floods above a selected base without regard to number within any given time period. The floods are numbered with respect to size, beginning with the highest as number 1. The base is generally selected as equal to the lowest annual flood so that at least one flood in each year is included. In a long record, however, the base is usually raised so that on the average only three or four floods a year are included. The only other criterion followed in the selection of the floods is that each peak be individual; that is, be separated by substantial recession in stage and discharge.

An objection to the use of the partial-flood series is that the floods listed may not be fully independent events, that is, one flood sets the stage for another. A related objection is that closely consecutive flood peaks may actually be one flood, since the damage is caused by the highest and the associated peaks may only have indirect or secondary effects on the losses.

The greater number of floods listed in the partial-duration series is commonly considered an advantage particularly when the record is short. However the greater number of points are at the low end, and the points at the upper end are generally identical with those in the annual-flood series.

A plotting of the floods for a stream by both methods, by any technique that may appeal to the analyst, will show equivalent results for the larger or less frequent floods, whereas for the smaller floods, the annual-flood graph will give results consistently below that of the partial-duration series.

Consider the one-year flood. For the annual-flood series, this is represented by the lowest of the annual floods. For the partial-duration series, this is commonly taken as the Nth flood in an N-year record. Obviously, the first is less than the second.

In the first case the one-year flood is that which may be equaled or exceeded in any year. In the second case it is that which has a mean expectancy, ϵ, of one in a year.

The probability of recurrence of a flood equal to or greater than magnitude m is in general $P = m/nN$, where n is the average number of floods per year, N is the total number of years of record, and m is the order of magnitude beginning with the highest. In the annual-flood series, $n = 1$ hence $p = m/N$. In the partial-duration series it is not necessary to define n, since the equation $pn = \epsilon$, defines the annual expectancy of recurrence of a flood that is equal to or greater than magnitude m. Hence in this case $m/N = \epsilon$.

If there are n flood peaks a year on the average, distributed randomly among N years, consider

Table 1--Relationship between flood expectancies in the partial-duration series and the probability of the corresponding flood as an annual flood

Expectancies partial-duration series m/N	Probabilities as annual floods	
	$p = e^{-m/N}$	$1-p = 1-e^{-m/N}$
2.0	0.135	0.865
1.0	0.368	0.632
0.69	0.500	0.500
0.50	0.606	0.394
0.20	0.819	0.181
0.10	0.905	0.095
0.05	0.951	0.049
0.02	0.9802	0.0198
0.01	0.99005	0.00995

Table 2--Relationship of recurrence interval of floods on the two bases

Partial-duration series	Annual floods
yr	yr
0.5	1.16
1.0	1.58
1.45	2.00
2.0	2.54
5.0	5.52
10	10.5
20	20.5
50	50.5
100	100.5

a flood of average expectancy $m/N = \epsilon$ (that is, expectancy that the flood will be of magnitude m or greater in a year). Then the probability of any flood being of this magnitude or greater is ϵ/n, and the complementary probability of a flood equal to or less than magnitude m is $1 - \epsilon/n$. Accordingly the probability of a flood of magnitude m being a maximum of the n floods in a year will be $p = (1 - \epsilon/n)^n = e^{-\epsilon}$, provided ϵ is small compared with n. The value of p therefore represents the probability of a flood of magnitude m, being an annual flood, and ϵ represents its expectancy m/N, among all floods in the partial-duration series. The value of $1 - p$ equals the probability of a flood of magnitude, m, being equalled or exceeded in the annual-flood series.

Table 1 may be constructed to show the relationship between flood expectancies in the partial-duration series and the probability of the corresponding flood as an annual flood and may be used to plot a partial-duration series on probability graphs. The third column gives the computed probabilities corresponding to observed expectancies listed in the first column. From this table we may also

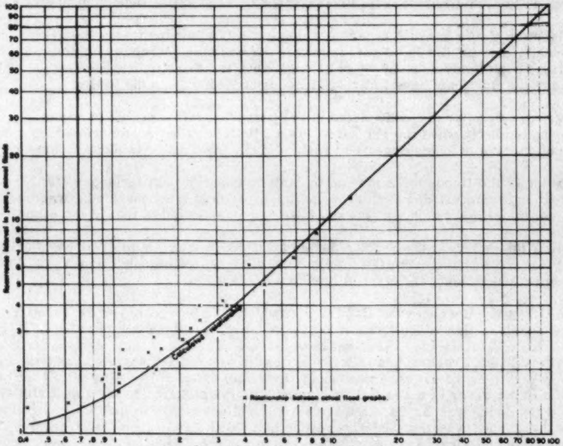

Fig. 1--Study of relationship between recurrence interval, partial-duration series and annual floods construct Table 2 to show the relationship between recurrence intervals of floods in the partial-duration series and as annual floods. The items in Table 2 are the reciprocals of corresponding items in the first and third columns of Table 1.

It will be noted that the two scales differ markedly for the smaller or more frequent floods, but are nearly equal for the higher floods. An annual flood is the maximum of all floods in a given year whereas a flood in the partial-duration series is selected as exceeding an arbitrary base and without reference to the number of other floods in the year. However, since a large flood is apt to outrank any other flood in the year in which it occurs, the recurrence intervals of great floods are closely the same in both scales.

The Tables were computed on the postulate that floods occur as completely independent events. Floods rarely behave according to the strict definition of randomness implied. Hydrologists recognize a persistence or interdependence in floods. Accordingly, there are deviations from random distribution, chiefly in the direction of greater grouping of the larger discharges, so as to make the items in the first column somewhat low.

Figure 1 shows the relationship indicated by Table 2. Also shown are a few points taken by comparing partial-duration series with annual floods for a few actual cases. The plotted points tend to plot above their calculated positions.

There is an important distinction in meaning as between the recurrence interval of these floods. In the annual-flood series the recurrence interval is the average interval in which a flood of given size will recur as an annual maximum. In the partial-duration series, the recurrence interval is the average interval between floods of a given size regardless of their relationship to the year or any other period of time. This distinction remains, even though for large floods the two approach numerical equality.

U. S. Geological Survey,
Washington, D. C.

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PROGRESS OF THE EUROPEAN TRIANGULATION ADJUSTMENT

C. A. Whitten

Abstract--The International Association of Geodesy is sponsoring a project for the readjustment of the triangulation of Europe. The adjustment will be made in two phases; the first phase consisting of a network of arcs adjusted onto the Central European adjustment, and the second phase a final adjustment with all possible refinements. Seven countries of southwestern Europe have furnished records to the Army Map Service for the computation and adjustment of the first phase.

At the 1948 Meeting of the Section of Geodesy, Floyd W. Hough reported on the readjustment of the European triangulation. His report contains the record of the progress that had been made by the Army Map Service and the International Association of Geodesy for accomplishing this project. A Special Committee had been established by the International Association with representatives from all of the countries having membership in the International Union of Geodesy and Geophysics. At a meeting of this Committee in 1947, a general plan was developed for the readjustment of the triangulation. The adjustment would consist of two phases. The first phase would be the adjustment of the nets of the various countries into a continental network using the results of the Central European Adjustment as a basis of control and datum. The second phase would be a final adjustment with all data reduced to the best spheroid that could be determined and all possible refinements used in the calculations. It was agreed that the computations for the first phase would be made in the United States under the general direction of the Army Map Service with the U. S. Coast and Geodetic Survey making the calculations required for the adjustment. As one of the American representatives of this Committee, I am giving this report to show the progress during the past twelve months.

At the Oslo Meeting of the International Union of Geodesy and Geophysics in August 1948, the problem of the readjustment of the triangulation in Europe was presented for discussion at meetings of the Section of Triangulation and the Special Committee.

At one of the meetings of the Section of Triangulation, where the subject was discussed, it was apparent that representatives of some countries were opposed to any recomputation of their control data. In some instances this attitude was based upon the fact that their triangulation had been recomputed in recent years or that their national net was incomplete. Representatives of seven nations of southwest Europe were in agreement and were ready to proceed in adopting an agreement for the readjustment of their triangulation.

At a special meeting of representatives of these seven countries - Netherlands, Belgium, France, Spain, Portugal, Italy, and Switzerland - and representatives from the United States, a general plan for the adjustment was unanimously adopted. A copy of this agreement is given below:

International Association of Geodesy

Plan for an agreement on the subject of the adjustment of the European geodetic net (West bloc).

The agreement which follows was established between the following seven nations: Netherlands, Belgium, France, Spain, Portugal, Italy, and Switzerland.

(1) The seven nations indicated above decide to undertake a provisional calculation of the whole of their primary triangulations, in their present state, without planning new observations.

(2) This calculation is designed to serve as a first approximation with a view to a calculation of a more scientific character which will be undertaken later by methods which remain to be studied in detail.

(3) It will be made on the Hayford ellipsoid, starting from elements pertaining to the Central European bloc recently calculated under the direction of the Army Map Service of the U. S. A.

(4) The seven nations indicated above agree to entrust the proposed calculation to the Army Map Service which will bear all the costs. The A.M.S. may use the method of its choice (in principle the method called Bowie improved) and proceed with the calculations in collaboration with the Coast and Geodetic Survey. The A.M.S. estimates that it will require 18 months after the elements of the observations have been furnished.

(5) These elements of observation should include azimuth observations, lengths of bases, and astronomical stations and Laplace points. The greatest precautions will be taken for stations reoccupied at many intervals, and especially for the junction stations between adjoining nations.

(6) In principle the Central Bureau of the Association will undertake to assemble the data pertaining to the execution of the calculation. Nevertheless certain nations may, if they so desire, furnish their data directly to the A.M.S. In this latter case the Central Bureau would intervene only to assure a necessary homogeneity for the junction vertices only between the triangulations of two adjoining countries.

(7) Whenever the calculations will be finished the representatives of the seven nations will meet anew, in common with the representatives of the U. S. A., to decide on the manner in which the results will be used and published.

The Association of Geodesy keenly hopes that an agreement may be entered into for the integral communication of the results to the seven participating nations. It will direct all its efforts in this direction. If an agreement in this direction cannot be entered into, the results will be communicated to each nation only for its own net. They will be communicated to other nations only by special agreement. But the seven nations bind themselves from the present time to authorize the publication, with an approximation to be determined (0.5" for example), of the geodetic coordinates of all the astronomic points in a manner to tend to the establishment of a net of the deviation of the vertical, which strictly speaking is the essential scientific end for which the present work is undertaken.

Representatives of other nations of Europe are still very interested in the project, and it is quite probable that most of these countries will arrange to have their triangulation adjusted into the European net at some later time.

In the discussions which took place in Oslo, the hope was expressed that the records, which would be needed for the adjustment, would be delivered to the Army Map Service by January 1, 1949. Early in 1949 the required records from the various countries were received. The preliminary computations are under way at the present time (April 1949) with the formation of condition equations actually begun for some portions of the network.

In the preliminary discussion it had been thought that a modification of the Bowie method of adjustment would be the most practical for the European net. After the data for the various countries were received, it became apparent that this plan would not be entirely satisfactory. In many instances there were no azimuths or bases in the junctions of the various arcs of triangulation. The Bowie method of adjustment requires that length and azimuth control be available for all junction figures. In view of this it was decided to make a simultaneous adjustment of all the triangulation in southwestern Europe. At the present time it is not known what the total number of equations will be, but an estimate has been made that there are about 2000 conditions to be satisfied.

A few years ago it would not have been feasible to consider solving a set of 2000 simultaneous equations of a triangulation adjustment. The improvements that have been made in high-speed computing machines in recent years now make it possible to solve such a set within a reasonable period of time.

It has been estimated that the first phase of the readjustment will be completed by June 30, 1950. By careful selection of arcs it will be possible to obtain an adjustment that should meet all engineering and mapping requirements. Since it will probably be many years before the countries of Europe are ready to readjust in accordance with the second phase of the plan, it is highly desirable that this first phase be as rigorous and accurate as possible.

The representatives of the countries of Europe have been very cooperative in assembling and delivering the required data and have shown a high respect for the direction of the project by the Army Map Service, and the technical assistance given by the Coast and Geodetic Survey.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

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PROGRESS REPORT OF THE JESUIT SEISMOLOGICAL ASSOCIATION

James B. Macelwane, Ross R. Heinrich,
Florence Robertson, and Joseph A. Volk

In the course of the year 1948, 14 member stations of the Jesuit Seismological Association were in operation and at the University of San Francisco a fifteenth was constructed to be put into operation in 1949.

General status--The station at Weston College was formally adopted as the Seismological Department of Boston College. Substantial progress was made on the new seismological building at Weston which will house, when completed, the six Benioff components and other earthquake station apparatus, and in addition the seismic prospecting equipment and the offices and shops. A new reflection prospecting truck was built by Daniel Linehan and his associates and equipped with a new Century recording unit and other new facilities. Many overburden and water supply studies were made by Linehan, especially for governmental, state and municipal agencies.

At Fordham University Joseph Lynch and his associates have recently laid out a tripartite station equipped with critically damped Sprengnether seismographs resonating with microseisms whose periods are in the neighborhood of one to three seconds which they have been studying for some time in their other records. Georgetown has plans for a new station on the campus when construction becomes feasible. The station at Canisius College, Buffalo, is now completed with two long-period Sprengnether horizontal components, a Sprengnether short-period vertical and a Galitzin-Wilip long-period vertical component, besides the small Wiechert and the long-period Wood-Anderson seismograph. A special feature of the station is a light-proof housing of the recording units so that the seismographs on their piers may be viewed through a glass door from the main corridor. At John Carroll University in Cleveland the new station was placed in operation with one short-period vertical and two short-period and two long-period horizontal-component Sprengnether seismographs and the small Wiechert seismograph. Many seismologists had an opportunity to see the station layout on the occasion of the meeting of the Eastern Section of the Seismological Society of America at John Carroll University in June, 1948. The most recent activity of the station is the measurement of blast vibrations. At Marquette University in Milwaukee, Wisconsin, plans are being matured for a modern station suited to the alluvial foundation of the City. Similarly, at Loyola University in Chicago, a modernization of the station is planned and a considerable part of the necessary funds has been collected. At Regis College in Denver, J. V. Downey, has been operating the two Macelwane-Sprengnether long-period horizontal components throughout the year and has secured good results. It is a general experience that very long period instruments of high sensitivity require considerable time to settle down and are peculiarly subject to disturbances caused by changes in relative humidity. The station at Mount St. Michael's College of Gonzaga University in Spokane has an excellent foundation on a massive flow of Columbia River basalt lying very near the granite. The two long-period Wood-Anderson seismographs lent to the station through the Jesuit Seismological Association by the University of Wisconsin have given excellent records during the year. The small Wiechert has always recorded the stronger shocks very well. At the University of Santa Clara, John H. Weber has been experimenting with different types of suspensions for the short-period Wood-Anderson seismographs. The three Galitzin-Wilip components have maintained their record of excellent performance. Weber's monthly report from Santa Clara is usually the first to be received at the Central Station. Going now to Loyola University of the South at New Orleans, Karl Maring has overcome the difficulties he had been experiencing with the short-period Sprengnether vertical seismograph. Its records, as mentioned previously, were constantly disturbed by high frequency vibrations. By increasing the free period of the seismometer from one second to two seconds and matching the impedance against a four-second galvanometer, excellent records of the first preliminary phases are obtained. The high frequency vibrations have disappeared, but at certain times strong vibrations of longer periods and of unknown origin appear on the records. At Spring Hill College, Spring Hill, Alabama, the McComb-Romberg horizontal component seismographs are working very well in the hands of Louis J. Eisele.

The St. Louis University stations at Little Rock, Arkansas, and Cape Girardeau, Missouri were originally equipped with the only Wood-Anderson of their type, having gravity drives and barrel focused cylindrical lenses mounted on the front of the seismometer housings. Both of these features have given so much trouble over the years that the drive governor was placed on a diamond-point bearing and the seismometers have been completely remodeled by the Sprengnether Instrument Company using a gold ribbon suspension. These instruments are shown in Figure 1. Both of the stations were out of operation during the year.

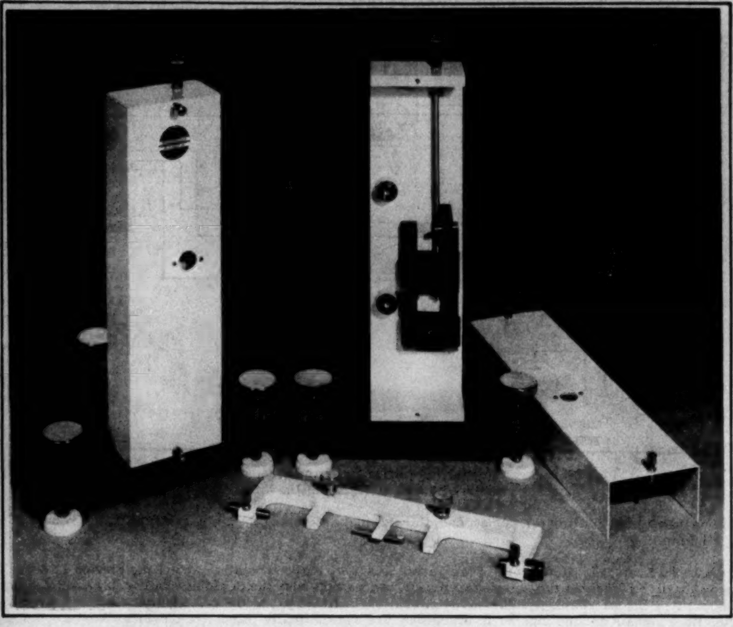

Fig. 1--Sprengnether-Wood-Anderson torsion seismometer for recording earthquakes

Time signals at the St. Louis Station--One of the major problems which confronts the natural earthquake seismologist is that of obtaining an accurate reference time for observatories located at widely spaced points all over the world. The various governmental agencies have cooperated with scientists by broadcasting the correct GMT at predetermined intervals. Most of us in the United States find either the time service furnished by the United States Naval Observatory over NSS or the signals broadcast by the Bureau of Standards the most satisfactory for use in seismological work. However, each seismological station must provide its own means of receiving these time signals and of recording them on their seismograms.

In most instances, the seismographs are located in vaults in more or less isolated places away from man-made disturbances. Hence either some sort of an automatic cycle timer must be provided at the station to turn the radio receiver on and off at predetermined intervals, or the receiver must be operated at some distant point. Because of the variations in the apparent frequency of the 9425 kc signals of NSS as picked up at St. Loiuis, Missouri, it is found to be necessary there to rely on manual tuning.

Three problems present themselves to the seismologist: first, that of amplifying the signals sufficiently to operate the timing relays ordinarily used on the seismological recording drums; secondly, that of prolonging without interfering with its onset, the output signal for a sufficient length of time to make it discernible on seismograms obtained on recording drums having a peripheral speed

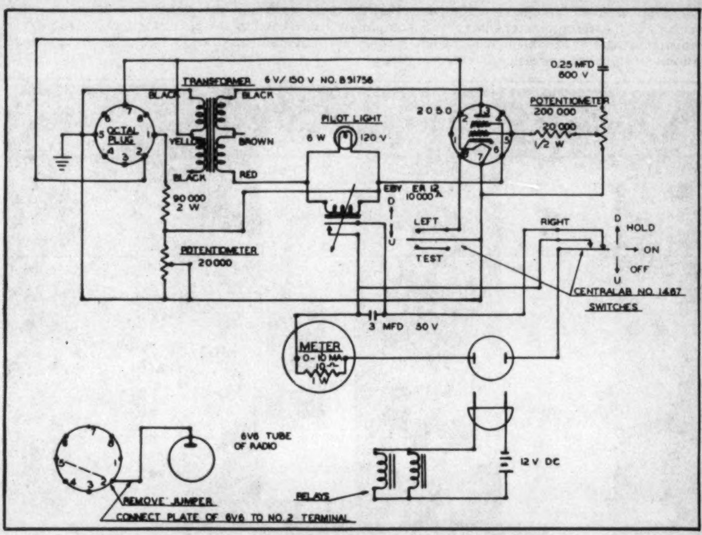
TRANSFORMER 6 V/ 150 V NO. 831756
BLACK
BLACK
YELLOW
BROWN
BLACK
RED
OCTAL PLUG
90 000 2 W
POTENTIOMETER 20000
PILOT LIGHT
6 W
120 V
2050
0.25 MFD 600 V
POTENTIOMETER 200 000
20 000 1/2 W
EBY ER 12 10000 A
D
U
LEFT
TEST
RIGHT
D
HOLD
ON
OFF
U
CENTRALAB NO. 1467 SWITCHES
3 MFD 50 V
METER 0-10 MA 10 ~ 1 W
6V6 TUBE OF RADIO
12 V DC
RELAYS
REMOVE JUMPER
CONNECT PLATE OF 6V6 TO NO. 2 TERMINAL

Fig. 2--Volk radio relay amplifier for transmission of time signals over leased line at St. Louis University

of one-half to one millimeter per second; thirdly, that of keeping the time-constant of the relays at a minimum.

At St. Louis, the paper work of the Jesuit Seismological Association and of the Station is done at 3621 Olive Street but the seismograph vault is located under the St. Louis University Gymnasium about three blocks away. A short wave National radio receiver, Model NC 173, is used to pick up the NSS time signals and the manner in which they are automatically transmitted over a Western Union leased line to the seismograph vault may be of interest.

Figure 2 is a diagram of the circuit designed by Joseph A. Volk. It shows the methods employed both to amplify the time signals sufficiently to operate the seismograph relays at a distance of three blocks and to prolong the output of the signal sufficiently to be visible on the seismograph records.

The receiver is provided with an outlet in the form of an octal socket at the back of the chasis. The only changes necessary are to remove the jumper from terminals 2 and 5 of the octal output and to connect the plate of the Beam Power Amplifier Tube 6V6 to terminal 2. The output of the receiver is then fed to the control grid of a thyraton, type 2050, the thyratron being used with an inductive load in a more or less conventional way. The positive peaks from the time signal make the grid of the thyratron sufficiently positive to cause the tube to become conducting and hence to fire suddenly. This flow of current closes the relay and thereby places a potential difference across the seismograph relay line. When the radio signal ceases, the grids again become negative so that during the next following cycle of the 60 cycle AC of the plate input the 2050 tube ceases to fire and hence is non-conducting as the plate voltages approach zero. This causes the relay to open. The 0.25 MFD condenser will then be discharged, thus causing an additional current flow in the external relay circuit.

In this way, only a small control current is required to cause a rather large plate current to flow; and the required prolongation of the signal is obtained. The threshold firing potential can be changed by means of the potentiometers making it possible to clip off some of the static peaks and thereby eliminate them from the relay circuit. By the insertion of a 1000 cycle band pass filter in the input circuit, the signal-to-noise ratio may be still further improved.

For convenience in operation, two Centralab switches are provided: one for testing the continuity of the overall circuit to the seismometer relays, and the other for disconnecting the automatic output of the receiver to the seismo-relay line. The first switch permits manual control of the closing of the relays in case of a fading signal. The second permits the radio to be used for ordinary receiving or other purposes without disturbing the seismograph records.

Changes at the Florissant Seismograph vault--During the summer of 1948, the electrical circuits at the Florissant Seismograph vault were modernized as shown in Figure 3: First, beginning with the input line to the vault, two new 220V-110V, three-phase transformers, General Electric 76G109 were installed; secondly, in order to equalize and/or isolate the load, the ceiling lights and the Curtis Dehumidifier were placed on one line, the 110 AC outlets on the seismograph piers on another, the radio on another, the seismograph lamps on a fourth, and the timing amplifier to be described below on still another; thirdly, all cables in the seismometer piers were replaced, using 10 and 12, solid, well-insulated wires for the AC lines, and good quality, plastic-covered, shielded microphone cable for the timing circuit and for the interconnections between the Galitzin-Wilip seismometers and their recording galvanometers; fourthly, four-prong Jones plugs and sockets were installed at each recording drum to provide the necessary connectors for the recording light voltage as well as the timing impulses; fifth, the Shortt synchronome master clock was put into operation; and sixth, an electronic timing relay circuit was installed.

At the present time the station is operating two triple recorders made by the Sprengnether Instrument Company and two of the single Henson Recording drums. The Henson timing relays are Western Electric 111 high impedance type with a flag of optical glass which is deflected into the optical path of the recording light beam to provide refraction of the light spot and thus print a visible line on the record during the signal. The two triple drums have a right angle prism, through which the recording light passes, mounted on the armature of an electro-magnet. An electric current through this electro-magnet tilts the prism and hence the light beam, thereby making visible-line time marks on the photographic records.

The Sprengnether relays were modified so as to provide good and dependable insulation of the coils and greater efficiency of the magnetic path. The coils were rewound. Each electromagnet now consists of two coils of 34 AWG enameled copper wire having a DC resistance of about 40 ohms each.

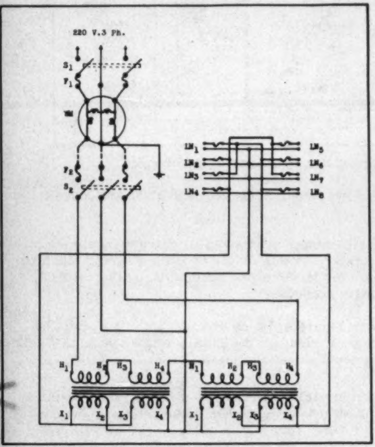

Fig. 3--Line distribution panel wiring of Florissant vault

To transmit the half-minute time signals from the Shortt master clock, the hour signal from the auxiliary dial controlled by the synchronome, and the radio time signals from NSS to the seismometer relays, a timing and electronic relay circuit designed by Joseph A. Volk of the St. Louis University Department of Engineering, was installed (see Fig. 4).

Actually, the electronic relay performs two functions. It furnishes the DC current to operate the seismometer relays when triggered by an impulse from the clock or radio; and it supplies a trickle charging current to the eight volt battery for the Shortt clock. This trickle charging current supplied from V_4 thru R_8R_{12}, and PL is automatically adjusted to the condition of the battery.

The Shortt synchronome was designed to operate on a current of 330 ma supplied by a storage battery. This feature has been retained so that the clock would not be stopped if a temporary failure in the 110 volt AC power were to occur. However, the trickle charging feature was added to eliminate the nuisance of replacing batteries for charging, as well as to improve the efficiency of the circuit. Formerly, as the battery potential dropped the clock would apparently lose time because of the delay in the time impulses which were

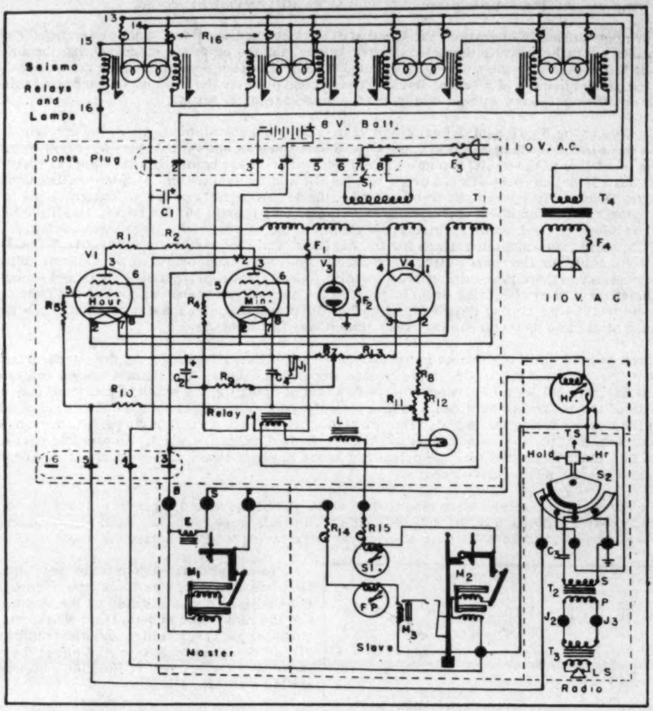
13
14
15
16
R16
Seismo Relays and Lamps
6 V. Batt.
110 V. A.C.
Jones Plug
1
2
3
4
5
6
7
8
F3
S1
T1
T4
F4
110 V. A C
C1
R1
R2
V1
V2
V3
V4
F1
F2
Hour
Min.
R5
R4
R7
R13
R8
C2
R9
C4
J1
R10
R11
R12
Relay
L
Hr.
TS
Hold
Hr
S2
B
S
E
M1
R14
R15
ST
FP
M2
M3
C3
T2
P
J2
J3
T3
LS
Master
Slave
Radio

Fig. 4--Schematic layout of the timing and electronic relay circuit

sent out; and eventually it would stop due to lack of synchronism between the slave and master clocks.

The prolongation of the time-constant of the half-minute marks can be changed by simply turning the knob of the potentiometer R_7 of the electronic relay. In this manner the time during which current will flow in the seismometer relays, and hence the length of the time mark on the records, can be varied from a fraction of a second up to thirty seconds.

To explain the operation of the circuit shown in Figure 4, let us divide it into five parts, beginning at the top of the diagram; (1) the seismometer relays; (2) the battery which operates the clock; (3) the electronic trigger unit; (4) the clock, master and slave; and (5) the radio.

The two Western Electric relays are connected in parallel with a 220 ohm, one watt resistor. This unit is then connected in series with the six modified Sprengnether seismometer relays as shown at the top of the diagram.

The synchronome clock diagram is given for convenience in the lower portion of the figure, the designations being those used by Hope-Jones himself. The Florissant master clock has been inoperative for a number of years. It was found, after measuring the resistances and impedances of the different portions of the circuit, that the inductance of the slave circuit was too small in proportion to its resistance thereby giving too small a time constant to the L-R circuit. In other words when the two pendulums were sufficiently synchronized for the master to control the slave mechanically, the electrical relations were so far out of phase that the synchronizing relay failed to operate within the required time interval. This again meant that the master clock could do neither of its tasks of controlling the rate of the slave clock nor the instant at which it sent the time impulse to the seismometer relays. In order to eliminate this difficulty, the inductance L (see middle of Fig. 4) was placed in series with the other inductances of the slave clock. At first glance, it might appear that the inclusion of this additional inductance as well as the relay shown just to the left of L would introduce a time-lag in the timing impulse. Actually, it eliminates one. The relay was inserted to isolate the clock from the amplifier and/or remainder of the time-circuit; hence, its electrical properties were also included in the overall design. By including the inductance L and the relay in the slave clock circuit, the actual time impulse is now controlled by the master clock, not by the slave; but these inductances are in the slave circuit and not on the master clock circuit. Hence, any time-lag which might be expected as a result of the high inductance of the clock circuit is no longer present in the output circuit through terminals 13, 14 and 15 of the Jones plug-socket connections.

In the installation of the equipment at the Florissant vault, the hour-dial was mounted on the wall in the outer or developing room above the short-wave radio. Such an arrangement made it much more convenient to transmit the radio time-signals to the seismometer relays over the same line as that used for the clock-hour marks and thus eliminated the necessity of another line through an already crowded conduit. As seen in the lower right hand side of Figure 4, a three-way switch S_2 has been installed on the side of the radio chassis. When the switch is in the position marked Hr the hour dial is in the output circuit. When in the position marked TS, the hour clock is disconnected and the output of the short-wave National receiver is automatically connected to the seismometer relays. Finally, when the position marked Hold, both the hour dial and the radio are disconnected and the relays may be operated manually for any reason desired.

The amplifier proper is shown within the dashed lines in the central portion of Figure 4. V_1 and V_2 are thyratrons 2050. As long as they are conducting, current will flow through the seismometer relays. The two tubes may work together or independently. V_1 is used to transmit the hour, the radio, or the manually controlled signal to the seismometer relays; V_2 transmits the half-minute time-signals from the master clock to the seismo-relays.

In operation, the control grids of the tubes are at a negative potential with respect to the cathode

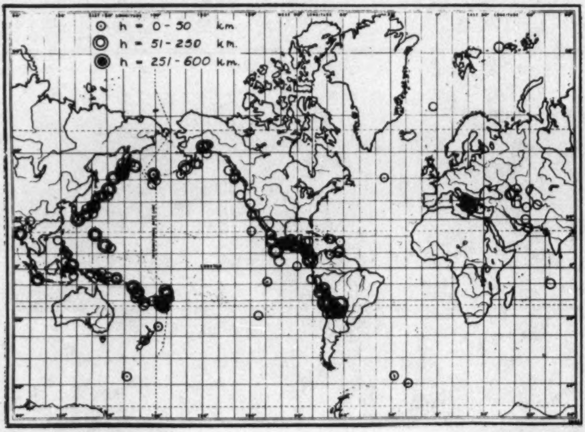

Fig. 5--Epicenters of earthquakes in 1948 located by the Central Station of the Jesuit Seismological Association so that the tubes are non-conducting. A signal from the clock closes the isolation relay, thus removing the bias from the control grid of V_2. This permits a DC current to flow from the power supply through the seismo-relays and V_2. At the same time the capacitor C_2 is being charged. C_1 is placed across the relay line to smooth out the DC pulses from the power supply and thereby eliminates chatter. After the isolation relay contact has opened because of the passage of the signal from the clock, current will continue to flow in the seismo-relay circuit until C_2 and hence the control grid of V_2 is charged sufficiently negative with respect to the cathode to prevent V_2 from firing at the next positive power supply impulse. In other words, the charge on C_2 places the required negative bias on the grid of V_2 to make it non-conducting. The clock impulse shorts out this capacitor by closing the isolation relay, thus causing C_2 to discharge and thereby removing the bias on the grid of V_2. V_2 starts to fire and continues to be conducting until the charging current from V_4 thru R_{13}, R_7 and R_9 causes C_2, and through it the control grid of V_2 to become sufficiently negative to prevent conduction through V_2 at the next positive pulse from the power supply. The time required for C_2 to charge is governed by the time constant of the C_2-R_9-R_7 circuit. This of course determines how long the current will flow through the seismometer relays.

An impulse from the hour dial over-rides the negative bias placed on the control grid of V_1 from V_4 through R_8, R_{11}, R_{10}, and R_5 and hence permits it to become conducting in a similar fashion.

The Central Station--The Central Station has operated, as in the past twenty-four years, on the three-cornered arrangement with Science Service and the United States Coast and Geodetic Survey and has published 139 numbers of the Preliminary Bulletin during the year. In these were given 158 tentative epicenters which are located on the map (see Fig. 5). In 1948 there occurred three very deep earthquakes with focal depths of about 600 km, one east of the Andes in Argentina and two in the southwestern Pacific near the Tonga Islands.

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REVIEW OF CANADIAN PACIFIC OCEANOGRAPHY SINCE 1938

John P. Tully

Introduction--Until 1943 oceanography on the Canadian Pacific Coast was sponsored by the Fisheries Research Board, and was directed entirely to fisheries objectives. From then until 1947 the facilities were diverted to naval purposes under the direction of the National Research Council of Canada. In 1946 the Joint Committee on Oceanography was formed by pooling the requirements and allotments of the Fisheries, Navy, and National Research Council in this field of research. Atlantic and Pacific Oceanographic Groups are established with headquarters at the respective Biological Stations and vessels manned and operated by the Navy. Technical assistance and equipment is provided by the National Research Council. This interdepartmental cooperation has greatly increased the horizon and capabilities of Canadian oceanographic research.

Most Canadian oceanographic studies in the Pacific have been located in the coastal regions and the inland seaways, and in consequence have been primarily concerned with the influence of fresh water in the sea and related phenomena.

The Fraser River project--The influence and limits of the Fraser River in the sea have been the subject of investigation by Canadian and United States oceanographers for the past twenty years. These include the studies by the University of British Columbia, the University of Washington, the Pacific Biological Station, and the Canadian Navy. These data are being consolidated into a coherent digest by the Oceanographic Laboratories at the University of Washington and the Pacific Oceanographic Group.

The Fraser River outflow system contains one of the wealthier fisheries of the Pacific coast, and is the subject of considerable fisheries research. Further, the system provides a wide variety of oceanographic conditions with virtual temperature gradients representative of Arctic, Temperate, and Tropical seas. As such, it is of primary importance as a region for naval underwater research.

It was found that the Fraser River spreads out in Georgia Strait, most of the water moving anticlockwise around that basin, mixing with the underlying sea water en route. It passes to the sea through a region of extreme turbulence in the Washington Archipelago where the 30 to 40 ft depth of brackish surface water, originating in the Fraser River outflow, becomes mixed with about 600 ft of dense sea water provided by tidal circulation from the zone of upwelling along the ocean coast. Evidence of fresh water from the Fraser River is lost in this process, so that the outflow from Juan de Fuca Strait is more saline than the approaches to many of the smaller drainage systems in the vicinity.

The outflow from Juan de Fuca Strait is evidently maintained by a hydraulic head established in Georgia Strait and Puget Sound. Emerging from the strait it veers to the right and moves northwestward along the Vancouver Island shore. This stream is subject to annual variation correlated with the fresh water discharge from the Fraser River and the seasonal winds, which are southeast in the winter and northwest in the summer. Within a distance of approximately 30 mi the energy of the northwestward flow is dissipated in eddies, and the water is absorbed into the California Current offshore and moves southward in the oceanic circulation.

This research was interrupted by the Alberni project (see below) and the War. Preparation of the report for publication is now under way.

The Alberni project--In 1939 it was required to predict the state of pollution that would result from a proposed sulphite pulp mill to be established at the head of Alberni Inlet on the west coast of Vancouver Island. This seaway is typical of many of the "fjord type" inlets along the British Columbia and Alaska Coast which, oceanographically speaking, are two-dimensional estuary systems.

It was apparent that the only pollution character of consequence was the oxygen demand of the waste sulphite liquor. If pollution was to be avoided, it was necessary that the mill sewage should be displaced from the mill site to the open sea before the dissolved oxygen content of the inlet

waters was lowered 50 per cent.

An intensive oceanographic investigation showed that the fresh water from land drainage moved isostatically seaward. Owing to tidal energy it mixed with the underlying sea water en route, to form a brackish upper zone. The thickness and properties of this zone and the rate of seaward displacement of water through it were quantitatively related to the discharge of the principal river in the inlet. There is a converse movement of ocean water in the zone immediately below this, which provides the sea water to be mixed into the upper zone. Any fresh water transferred downwards is held isostatically adjacent to the boundary and preferentially returned to the upper zone in the mixing process. Consequently all fresh water leaves the inlet by way of the upper zone, and none accumulates in the lower.

Below the level of the threshold there is a deep zone in which movement is generated by frictional transfer of velocity from the overlying middle zone.

A hydraulic model of the head of the inlet was built in which the tide, the fresh and sea water, and the winds were represented. From this it was learned that the outflow of the river was a jet function, whose stream diverged until it occupied the whole width of the inlet. Seaward of this limit of divergence there was no transverse salinity gradient, and the system was effectively two-dimensional. The tidal and isostatic flow characteristics in the head of the inlet and the course of the effluent from various sewer outlets were studied in this model and confirmed by oceanographic observations and float experiments in nature.

From these studies it was evident that if the pulp mill sewage were diluted with all the wash water from the mill so that it entered the upper zone of the inlet, at approximately the density of fresh water, it would remain in the upper zone and be continually displaced seaward. This approach to the problem permitted the fresh water in the inlet to be regarded as a tracing solution, indicating the behaviour of the proposed effluent. It was concluded that no sewage would appear in the middle or deep zones which would therefore be free of pollution. If sewage were dumped in these zones, it would accumulate and eventually cause pollution.

The degree of pollution P was defined as the ratio of oxygen demand of the pulp mill sewage BOD to the dissolved oxygen supply DO. The tolerable rate of discharge of sewage into the upper zone was arbitrarily defined as the amount whose oxygen demand would not exceed 50 per cent of the oxygen supply. The pollution was considered tolerable when $P = BOD/0.5(DO) \overset{=}{<} 1$. This provided a quantitative definition of pollution which could be evaluated.

The normal oxygen content of the incoming fresh and sea water was observed, and the oxygen supply in the upper zone was evaluated from the observed proportions of each and their rate of displacement through the inlet. The oxygen demand of the pulp mill sewage was estimated from the known rate of oxidation of waste sulphite liquor and its concentration and age at successive intervals between the head and mouth of the inlet. The latter quantities were predicted from the relations between river flow and the quantities of sewage discharge, the proportion of fresh water in the upper zone, and the displacement.

It was concluded that the sulphite mill would be tolerable while the discharge of the principal river into Alberni Inlet exceeded 1600 cfs. The discharge was less than this during three months of the year, implying that mill operation would have to be curtailed, the sewage stored over the period, or the river discharge maintained by storing water when the river was high. Industry solved the problem by building a sulphate mill whose pollution potential was within the tolerable limits of the seaway.

This installation has been checked, and the degree of pollution is found to be well within the predicted limits. At the same time further expansion is limited by the remaining margin of tolerance between the existing and limiting degree of pollution.

It is to be remarked that in this case there was no problem arising from pulp fibers settling out, because the bottom of Alberni Inlet does not contribute to a commercial fishery.

This research is unique in that it undertakes to evaluate quantitatively the characteristics of an estuarial seaway in terms of river discharge, which is a readily observable monitoring factor. It provides a quantitative measure of pollution and shows how it may be evaluated from a knowledge of the properties of the pollutant, and the oceanography of the system. Finally, it offers a precedent for the prediction of the probable degree of pollution from industrial development, which in turn permitted adjustments to be made before the fishery was damaged.

The field work was done between 1939 and 1942, but development of the data was interrupted by the War and was only completed in 1948. The research is reviewed in detail in three papers, which are to be published as a Bulletin of the Fisheries Research Board of Canada (Ottawa):

(1) TULLY, J. P., Oceanography of Alberni Inlet.
(2) TULLY, J. P., Prediction of pulp mill pollution in Alberni Inlet.
(3) TULLY, J. P.; HOLLISTER, H. J.; FJARLIE, R. L.; and ANDERSON, W.; A hydraulic model of Alberni Harbour.

Chatham project--At the present time the Pacific Biological Station is making an intensive investigation of the sockeye salmon fishery associated with the Nass and Skeena Rivers. These are large rivers (2500 to 250,000 cfs discharge) entering the inland seaway (Chatham Sound) near the boundary between British Columbia and southeastern Alaska. A proportion of the salmon fishery occurs in Chatham Sound beyond the geographic limits of either river. An intelligent study of the fishery in the sound requires a knowledge of the influence and variations of the rivers in that area. The oceanographic problem is to determine the course and influence of these two rivers in the region, from the time of maximum river discharge (May) to the minimum (September), and the variations introduced by the prevailing winds, and tidal cycle.

The field investigation has continued from May 10 to September 10, and a preliminary report is in preparation.

Lighthouse project--A program of daily observations of the sea water temperatures and salinity was initiated on the Pacific coast of Canada in 1917 with one station. This number has been increased at intervals until the present total of eleven stations was reached in 1939. Most of the observations are made from coastal lighthouses; hence the project designation.

The seasons are shown in the temperature data, and the integral effects of land drainage are shown in the salinity records. The small fluctuations are attributed to wind effects, since offshore winds cause upwelling and a consequent decrease in temperature and increase in salinity. Onshore winds have the converse effect. The duration of any combination of conditions is indicated by corresponding steady states in the records.

Oceanographic surveys are tedious and costly undertakings, which cannot be repeated indefinitely, and from which the conclusions usually are not available before the observed situation has passed. However, it may be assumed in most cases that the oceanographic state is determined by the season, weather, tide, and runoff, whose integral effect is reflected in the conditions at one point in the region. Therefore oceanographic surveys are usually undertaken to observe type states in terms of the controlling factors, and the conclusions related to the appropriate lighthouse observations. This allows the recurrence of the observed state to be recognized from these data alone; that is, the lighthouse data serve to identify the conditions under which occasional oceanographic observations are made, their duration, and frequency of repetition. The daily observations provide a complete calendar of events in the coastal ocean and seaways, by which present data may be made applicable to the past and future.

It is the purpose of this investigation to accumulate these records as reference data for all other investigations in the Canadian coastal seas, to determine their significance as submarine climatological indices, to determine their relations, if any, with the success of coast fisheries, and to evaluate annual cycles and trends and geographical differences. Their use has been somewhat delayed by the War, but this process of examination is begun, and studies based on the data may be anticipated.

The data are being published in mimeographed volumes entitled Observations of sea water temperature, salinity, and density on the Pacific Coast of Canada, which may be obtained on application to the Director, Pacific Biological Station, Nanaimo, B. C. The volumes available at present are: (1) 1914-1934, (2) 1935-1937, (3) 1938-1939, (4) 1940-1941, (5) 1942-1943, and (6) 1944-1945. Volume 7 for 1946-1947 is in publication. Volume 8 will be for 1948, and thereafter the publication will be issued as an annual volume.

Pacific Oceanographic Group,
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(Manuscript received April 28, 1949; presented at the Thirtieth Annual Meeting, Washington, D. C., April 21, 1949; open for formal discussion until May 1, 1950.)

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OCEANOGRAPHIC RESEARCH AT THE U. S. NAVY ELECTRONICS LABORATORY

E. C. LaFond

General

Organization--The Oceanographic Studies Section of the U. S. Navy Electronics Laboratory at San Diego, California, was organized in 1946 to continue the wartime research previously conducted by the Division of War Research of the University of California. Since one of the main efforts of USNEL is the investigation of underwater sound and the development and evaluation of sonar devices, most of the investigations of the Oceanographic Studies Section are directed toward supporting underwater sound research. In connection with this work, however, research is also done on other phases of oceanography. Assistance contracts between USNEL and the Scripps Institution of Oceanography of the University of California and the Hancock Foundation of the University of Southern California provide close cooperation with these activities engaged in oceanographic research in Southern California.

Ship facilities--Adequate ship facilities for oceanographic research are available at the Laboratory. One of the ships is especially equipped for oceanographic work, with a large winch holding 20,000 ft of 3/8 inch wire rope, a hydrographic winch holding 20,000 ft of 5/32 inch wire rope, and two small bathythermograph-type winches with 3/32 inch wire rope. Other equipment includes an NMC-2 echo sounder, special navigation and positioning equipment, and a large laboratory space. In addition to operating from the vessels permanently assigned to the Laboratory, oceanographic observations and measurement are frequently made from ships of the Fleet. The mild Southern California climatic conditions permit year-around work at sea, and the unusual basin and bank sea floor topography offers a wide variety of readily accessible oceanographic environments.

Equipment--To date considerable effort has been expended in obtaining standard oceanographic gear and developing new equipment. Some of the new devices include a sonic device for obtaining information on the type of bottom [LAFOND, DIETZ, and KNAUSS, in press], an improved snapper-type bottom sampler [LAFOND and DIETZ, 1948], an instrument for measuring the temperature of bottom mud in situ, an improved type of gravity coring tube for sampling bottom sediments, and a current meter which will measure the direction and speed of currents, the temperature and depth, and record the results photographically. In addition, a Kullenberg piston corer has been obtained for testing and use. Underwater cameras have been extensively used and modified for special purposes and preliminary tests have been conducted with underwater television. An acoustical wave recorder and sound velocity meter have been developed and successfully used in sea studies. Under development are a conductivity-temperature-depth recorder for sea water and a stereopticon camera for sea surface pictures.

Program

Some of the oceanographic work accomplished during 1947 and 1948 is as follows.

Antarctic oceanography--Two representatives of the Oceanographic Studies Section participated in Operation Highjump (U. S. Navy Antarctic Development Project, 1947). A general report on the oceanographic observations made on this expedition from ships of the Western Task Group along the western Pacific and Indian Ocean sector of the Antarctic Ocean has been published [DIETZ, 1948a]. A special study of the Antarctic Convergence has also been prepared [PRITCHARD and LAFOND, in press]. In addition to the Antarctic work, some oceanographic data have been collected in the Arctic in the course of Navy training operations. The Laboratory is also furnishing assistance to the Arctic Research Laboratory, a cooperative project sponsored by the Office of Naval Research.

SOFAR--The installing and testing of the SOFAR (SOund Fixing And Ranging) air-sea rescue network in the northeast Pacific has presented many oceanographic problems. The physical properties of the sea permit sound to travel thousands of miles through a deep, low-velocity layer known as a sound channel. The oceanographic phase of the installation has been to choose suitable sites for the deep hydrophones to pick up these sounds and to find suitable cable routes to shore. This involved detailed surveys of the depth and strength of the sound channel and the bathymetry and bottom type. Four sites have been surveyed and three installations made.

A thorough test of the SOFAR network is now in progress. During the latter part of 1948, the first of a series of cruises was undertaken to investigate characteristics of the sound channel throughout the northeast Pacific. Hydrographic stations have been occupied and the sound channel evaluated by season and geographic position for depth and for suitability in SOFAR transmissions.

The use of SOFAR as an oceanographic tool to determine the average sound velocity in the sea, to investigate deep currents, to detect submarine landslides and volcanoes and to study other oceanographic and geophysical phenomena has been reported [RUSSELL, in press, a].

Sea floor investigation--Research is continuing on sea floor problems, including investigation of sediments and sea floor geomorphology [RUSSELL, in press, b]. Studies have been completed on certain features in the Pacific and Antarctic Oceans [DIETZ, 1948a; DIETZ, in press] and several investigations of sea floor features in the basin and bank region off Southern California have been made. Also, a special study was conducted of two deep flat-topped seamounts which rise from the deep ocean between the United States and Hawaii.

Internal waves--Investigations of the characteristics and cause of internal waves in being conducted. Work is progressing on an analytical solution to the Feldstadt internal wave differential equation for the case of a density distribution of the form $\rho = \rho_d - \theta\rho e^{(z - h)/m}$. This function can be fitted quite closely to most observed density distributions below the mixed layer. It is believed that a suitable solution in terms of a rapidly converging infinite series can be found. A three-ship observational program to determine speed, direction, period and other characteristics of internal waves has been carried on off Southern California.

Lake Mead--In cooperation with the Water Resources Branch of the U. S. Geological Survey and the Bureau of Reclamation, members of the Oceanographic Studies Section have conducted monthly surveys throughout the past year at Lake Mead. From the thermal and salinity structure the circulation and heat distribution of the lake is being determined. A further program is planned to compare observed and theoretical methods of calculating water losses. Accurately determined humidity, temperature, and wind gradients will be used to compute evaporation loss by turbulent transfer and the results compared to losses calculated by heat-budget and water-budget methods.

Sound scatterers in the sea--An investigation of zooplanktonic and nektonic sound scatterers in the sea has been made [DIETZ, 1948a and b] by correlating underwater sound records with net hauls. Special emphasis has been placed upon the diurnally migrating deep scattering layer, which appears to be composed of euphausids and possibly also of pelagic shrimps.

Other studies

Slicks--A study has been made of natural slicks which have been observed throughout the Pacific and Antarctic Oceans [DIETZ, 1948a]. The oily film has been collected and analyzed in the laboratory

Currents--A method of determining currents from bathythermograms has been devised from data collected on Operation Crossroads [LAFOND, 1949]. The vertical density distribution, necessary to determine relative currents, was obtained from bathythermograms by relating temperature to salinity in limited areas.

Technical Handbook--A chapter is being prepared for the Technical Handbook in Physical Oceanography, to be published under the auspices of the International Association of Oceanography, IUGG. The chapter will discuss the methods of processing physical oceanographic data ashore and present the most commonly used oceanographic tables.

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OCEANOGRAPHIC ACTIVITIES OF THE U. S. COAST AND GEODETIC SURVEY

Leo Otis Colbert

The United States Coast and Geodetic Survey has continued its work of surveying and charting the coastal waters of the United States and possessions. In carrying out that function, the Bureau is constantly adding to its fund of oceanographic and geophysical data as expressed in terms of depths of water, character of the sea bottom, the rise and fall of the tide, and the study of currents and physical properties of sea water.

We are continually improving our techniques for the collection of such data. This has been true notably with respect to the methods of depth measurement and the determination of position. Greater accuracy is being achieved in echo sounding through improvements in the time-measuring device and in operational techniques. The adaptation of electronics to horizontal distance determination has greatly enhanced the value of offshore hydrographic surveys for oceanographic and geophysical studies.

During the past year we have made further application of Shoran in our operations. In addition to its use by ships and launches for conventional surveys, it has been installed for the first time in wire-drag launches with satisfactory results.

An interesting phenomenon was noted in the Shoran-controlled hydrography in the Aleutian Islands that may have important possibilities in future operations. Instead of the usual limit of 55 statute miles for this area, on two occasions the ship Pioneer was able to extend control to distances of 70 to 143 statute miles from three ground stations. This is attributable to the peculiar atmospheric conditions existing at the time. Weather data are being collected that may be of value in determining in advance when it would be possible to conduct operations in a remote critical area under similar weather conditions.

The development of the Electronic Position Indicator, for offshore hydrographic surveying, has been reported to this body previously [COLBERT, 1948]. Thus far the use of the system has been confined to the Gulf of Mexico where the low coastline makes it particularly applicable. Hydrography has been controlled by this system to a distance of nearly 300 mi offshore from one of the ground stations. Tests are being conducted for the further refinement of the system involving new antenna design, circuit improvements, and study of meteorological conditions during test periods. It is hoped that the final design and operating techniques will become standardized during the 1949 field season. Over 10,000 sq mi of hydrography were accomplished in the eastern portion of the Gulf by the ship Hydrographer.

In Alaska, hydrographic surveys were continued in the Aleutian Islands, in Prince William Sound, and in the vicinity of Sitka. The first comprehensive survey of the vast area to the northward of the Alaskan Peninsula, begun last year, was continued in the Bristol Bay area and along the Arctic coast. Only parts of two months in the middle of the summer are available for hydrographic surveys because of the ice conditions. Bases from which to operate are practically non-existent and must be established by the party as the field work progresses. Recently, it was necessary for one of our Arctic field parties to establish a new operational base to the eastward of Point Barrow. This required four round trips, of 200 mi each, by caterpillar tractor train across ice and through blizzards with temperatures of -50°F.

As our combined operations move farther into the northern latitudes of the Arctic region we are experiencing ever-increasing difficulties. The shortness of the season, the difficulties of transportation, the low temperatures remain the most serious problems encountered, and with the special equipment required, increase the cost of the survey operations. Throughout this coastal region of Alaska, a systematic accumulation of comprehensive data relating to the geophysical characteristics, within the scope of the functions of the Bureau, is now being undertaken.

The program of running sounding lines across the Gulf of Alaska by Survey vessels while en route to and from their West Coast bases has been extended into the North Pacific Ocean. Seven thousand miles of these lines were run in 1948, bringing the total since the beginning of the project to 63,000 nautical miles. The positions of these lines are well determined from loran distances and from nume ous carefully taken astromonic sights by the hydrographers, followed by office adjustments of adjacent lines and cross lines. Several new submarine mountains have been revealed, some one-half mile to more than a mile high. The northwestern ends of several of the lines crossed the Aleutian Trench and depths as great as 4000 fm were obtained. On the southeastern end of one of these lines an indication was obtained of a continuation of the submarine scarp off Cape Mendocino, California, to a point 300 mi seaward.

Surveys in the vicinity of the Aleutian Islands developed a submarine canyon to the west of Kiska Island. The canyon is the most prominent on the south side of the chain. It indents the continental slope for a distance of 30 mi and has depths of 1000 to 2500 fm. To the north and northwestward of Kiska Island, the surveys, covering an area of some 5300 sq mi, disclosed a uniformly smooth and level ocean floor at a depth of 2140 fm.

Other hydrographic surveys were made along the Atlantic seaboard from Chesapeake Bay to the coast of Maine, and in certain inland waters, including Chesapeake Bay; the James River in Virginia; Point Judith Pond, Rhode Island; Boston Harbor; San Francisco Bay; Puget Sound; the Columbia River Lake Roosevelt; Wash.; Lake Pend Oreille, Idaho; and Clear Lake, Calif.

Interesting, although minor, configurations of submerged topography were revealed by a survey in Penobscot Bay, Maine. Numerous circular and oval depressions, 100 to 300 ft across and 20 to 30 ft in depth, were found in the approaches to Belfast Bay in 50-ft depths.

Experiments have been conducted at Buffalo Lake and Devils Lake, Washington, with echo sounding through surface ice. The projector and receiver units from a portable graphic recorder were placed in contact with the ice and water poured around the base of the units to effect a bond. The experiments demonstrated that as long as a good bond is maintained with the ice, soundings can be successfully obtained to a depth of 80 ft when the units are stationary. The units are, however, not sensitive enough to be used successfully in obtaining soundings when moving across the ice surface. Further experiments with other types of equipment are indicated. If this method of sounding should prove successful it will be a great boon towards facilitating hydrographic work in the northern portions of Alaska where ice conditions are prevalent for the major portion of the time.

Under the Philippine Rehabilitation Program, the survey work in the Islands was continued. Survey personnel directed extensive wire-drag operations in Manila Bay, various hydrographic surveys, and other survey operations. As part of the program a number of Filipinos are being trained each year for eventual taking over of the survey work.

Our tidal work has been greatly expanded. In addition to the data collected from stations in this country, we are receiving data through participation in special projects in other countries, including the programs of the Department of State and the Inter-American Geodetic Survey in Latin-American countries, and the program of the U. S. Corps of Engineers in the Pacific. These accumulated data will furnish basic information for the prediction of tides and for the study of tidal action in these area Records from over 120 tide stations are being received and processed.

To observe the characteristics of offshore tides, gages have been established on two of the oil drilling platforms which one of the oil companies has erected in the Gulf of Mexico. A cooperative tide station was also established at Long Branch, N. J., in connection with studies being made by the Beach Erosion Board.

Tidal records obtained by the Finn Ronne Antarctic Research Expedition were processed and analyzed.

Through the use of the Roberts radio current meter, detailed information on current movements were obtained in a number of localities, including some important Alaskan waterways. This is part of an expanded program of observing currents in conjunction with hydrographic surveys. Tidal current charts depicting the hourly movement of the current in Delaware Bay and River, were published in a series of 12 charts.

The comprehensive current survey of Tampa Bay, Florida, is still in progress. From results which have already been obtained, daily predictions will be published shortly of the current movement in the entrance to the bay.

The program of securing long series of hourly current observations at selected lightship stations along our coasts has been continued through the cooperation of the United States Coast Guard. The results of these observations, besides furnishing information for navigation, are an important addition to our fund of oceanographic data.

The program of observing temperature and density of the surface water at tide stations has been expanded with the growth of the cooperative tide programs in Latin America and in the Pacific Islands.

Work was continued on the formation of the seismic sea-wave warning system for the Pacific. As at present developed, the warning system consists of four Survey seismograph stations, the reports from which will definitely fix the epicenter of the producing earthquake; a network of tide stations in the Pacific some of which have seismic sea wave detectors; a seismic sea-wave travel-time chart; and a high priority communication system. The center of the system is the Coast and Geodetic Survey seismograph station at Honolulu. The quake of September 8, 1948 in the region of the Tonga Islands in the South Pacific provided an interesting test of the system's operation. The area was alerted, but as the wave reports came in it became clear that the wave would be small, and no warning was broadcast. The record showed that a seismic sea wave of six inches had arrived at the predicted time at the Honolulu tide gage.

A recent development in seismic study contains interesting added possibilities regarding the detection, location, and identification of submarine earthquakes. This involves the newly discovered fact that these earthquakes sometimes generate low-frequency sound waves peculiarly adapted for long-distance transmission through conducting layers of the sea water. These waves pass into the ground structure of oceanic islands and can be recorded on special seismographs shortly after the higher-speed all-ground waves arrive.

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REPORT OF THE RESEARCH COMMITTEE ON LAND EROSION, 1948-1949

W. C. Lowdermilk, Chairman

1949	1950	1951
Reed W. Bailey	Carl B. Brown	Paul C. Benedict
D. H. Eargle	Kenneth Segerstrom	Luna Leopold
W. D. Ellison	Herbert C. Storey	H. V. Peterson

Activities during 1948-1949 fall under the laconic expression, routine. With the cooperation of the U. S. Navy, W. D. Ellison has been able to continue his investigations of dynamics of raindrops. But, unfortunately, this most promising field of new discoveries and of evaluation of dynamics of the beginnings of erosion is being left fallow for the most part. Rotation may have its place in use of farm land, but rotation in research work breaks continuity and displaces workers, all of which retards productive progress in discoveries and evaluation of factors in the complex process of nature.

Nowadays scientists are discovering a new world and new forces in the atom, and in the minutia of nature. Dynamics of the raindrop open up a field of great possibilities and of profit. Present appraisals of erosional processes no doubt would be more clearly pointed up and strengthened by an adequate program of research in this phase of the broad subject. It is the pioneer fringe of erosion research in water erosion and deserves far more attention and support than it is getting.

G. W. Musgrave and other research workers of the Soil Conservation Service have related erosion of land slopes to the interaction of forces and resistances. They point out that in order to secure adequate control of soil erosion we need to match the force with the resistance in (1) magnitude, (2) time, and (3) frequency. The frequency of occurrence of excessive storms with respect to time must be known. Storms that produce more than 0.5-inch rainfall in 15 minutes, which are classed as excessive by the United States Weather Bureau, normally produce the greater part of the erosion. At Ithaca, N. Y., 21 such storms out of a total of 173 produced 65.7 per cent of the soil loss. At Clarinda, Iowa, out of 128 storms in the period 1933-1942, 18 storms caused 78 per cent of the erosio Furthermore, 54 per cent of the erosion on corn land occurred in May and June. Relatively good data are already available on the magnitude of the protection secured by various agronomic practices and the seasonal frequency with which it occurs. If a complete or factual analysis of the important elements in local problems is overlooked, however, it is likely that the wrong emphasis will be placed on the various factors. For example, a given area of cropland may have good rotations, adequate fertilization, good cover crops, and other favorable factors, but the spacing of crops and ground cover may be such that the one time of the year in which the ground is essentially bare is that time at which 50-75 per cent of the erosion-producing rains are expected to occur. Thus, the timing of measures is in error to the point where relatively little conservation is attained.

By correlating a large mass of experimental data, Musgrave has also developed a first approximation of the relative effects of the principal causal factors in sheet erosion, namely (1) rainfall, (2) slope, (3) soil, and (4) vegetal cover. The data indicate that the rate of erosion, in tons per acre of dry soil varies (1) as the 1.75 power of the maximum 30-minute rainfall of two-year frequency; (2) as the 1.35 power of the slope, in feet per hundred, and (3) as the 0.35 power of the length of slope, in feet.

By equating measured erosion rates for 19 different soils on which extensive data are available to a common 1.25-inch, 30-minute rainfall on a ten per cent, 72-foot-long slope with minimum vegetal cover, the inherent relative soil erodibility was found to vary from 0.03 to 0.96 inch per year. In other words, because of characteristic textural and structural differences of soils, an extreme variation of 33-fold in their erosion potential may be expected.

By far the greatest relative difference in rate of erosion was found to result, however, from the character and density of vegetal cover. Assuming the same soil, slope, and rainfall, the rate of erosion on land used for continuous row crops (such as uncontoured cotton, corn, or tobacco) was found to be more than 100 times as great as on land used for hay, pasture, woodland, and forest.

These research data give a basis for estimating the potential reduction in sheet erosion that might be achieved by modification of the causal factors. Although rainfall intensity and frequency cannot in themselves be changed, analysis of their monthly expectancy in any area gives a basis for planning maximum protection of the soil surface by cover crops, mulches, and other means, in those months when the erosion potential from rainfall is greatest. The effects of length and degree of slope indicate the relative need for measures such as terraces, diversion ditches, strip crops, and benching to reduce the effective slope and break it into shorter lengths. Inherent differences in soil erodibility suggest adjustment of land use so as to afford greater vegetal protection of more erodible soils and more use of less erodible soils for row crops. It indicates also possibilities for reducing the inherent erodibility by changing the soil structure through tillage practices and by plowing under cover crops, mulches, and manure. Lastly, differences in effects of vegetal cover emphasize the need for rotation systems of farming, use of cover crops, and conversion of some row-crop land to permanent cover.

New basic studies of wind erosion were begun by the Soil Conservation Service in western Kansas. Wind-intensity-duration curves for selected months based on a 74-year record at Dodge City, Kansas, were developed. Adjusted monthly averages of wind velocity were found to be amenable to study by probability methods. Wind-intensity-duration curves were developed for wind movement occurring during the month of April for selected years. The general pattern of these curves was found to be similar. An average dimensionless pattern of wind storms was derived from storms occurring during the monthe of April 1935. The peak of storm intensity was found to be at the mid-point of storm duration. The results of the study indicate that the problem of soil erosion by wind may be approached analytically by methods similar to those employed in the field of flood control.

Peterson reports studies of arroyo erosion in the Southwest. Gullies have been mapped in detail and their growth is measured by repeated remapping. This is a study that has been needed for many years. Although during the period of study no great growth in arroyos in valley fills of the study area can be reported, the study will no doubt in time disclose pulsatory phases of arroyo cutting. The first stage of arroyo cutting had taken place before mapping began. It may be some time before conditions combine to generate another phase.

One of the recommendations of the Committee is to hold a field symposium of students of erosion at the site of these studies. All aspects of the problem from character and amount of rainfall, vegetation cover, the valley fill, and runoff that causes erosion will no doubt be examined by appropriate specialists together that a full examination of the problem may be made.

Leopold is reviewing the arroyo problem and reports results of a study he has made over a number of years, in a significant paper in preparation, The Southwestern erosion problem. Leopold reviews the evidence and the several theories that have been advanced to explain the obvious increase of arroyo cutting in the Southwest since the occupation of the country by stockmen and farmers. To quote from a draft of the paper, "The concepts outlined in this paper point up the fact that hydraulically and physiographically, the Southwestern erosion problem is perhaps more difficult to solve than conservationists might have realized. The physiographic history indicates potential capacity of alluvial valleys to degrade. This is the crux of the geologist's contribution to the problem of erosion control policy. Whether one wishes to label the reason for this potential instability 'climatic change' is unimportant. But the impact of the geologist's message certainly has not been incorporated into erosion control policy during those years when large amounts of cash were being poured out for erosion works.

"The determination of primary benefits from control measures is not within the scope of this paper. The development of concepts of the type presented here should eventually provide a more solid foundation for assessment of costs and benefits in the study of engineering works affected by the erosion problem (in the Southwest)."

This paper, which the committee specially calls to the attention of students of erosion, emphasizes the need for a far more thorough study of the physiographic aspects of erosion than has thus far been given this problem. In the Symposium on Land Erosion at the General Assembly of the American Geophysical Union in 1941, [Trans., pp. 236-320, 1941], the concept of "physiographic engineering" was presented as necessary to an adequate approach to problems facing the country in fully utilizing as well as conserving its land and water resources.

Instead of pursuing such lines of investigation, so essential to an intelligent use of taxpayers' money, there has been a progressive reduction in interest in broad fundamental studies and increased pressure for more short-range studies that were advanced as immediately practical. This point of view denies to this generation and to generations to come the play of the research function.

For research should embody the prophetic function of society. In no other field is this more important than in the use of land and water. With rapid increase of population and stepped-up use of power machines and implements, the issues of conservation are swarming in upon society. Research to serve the country best must discover in the present situation trends, their relative importance, their direction, and the problems they will create in the future. Having discerned these problems before they are hard upon the country, investigations may be planned and carried out to find the facts that will be needed for solution of the problems in the offing.

This is important for it takes time to carry through scientific experiments that will yield valid results. If we wait until the crisis is upon us, hurry-up, makeshift studies or broad guesses will be used for the design of remedial measures. These may be wasteful, not only of taxpayers' funds, but of confidence of the public as well; and, as Leopold has shown, may fail and very likely will fail, as they already have in many cases, in being effective in treating a complex of factors.

The question naturally arises: Can the country depend on governmental agencies that are caught in the pressure of satisfying demands of victims of emergencies, that are subject to political pressure to act in haste and with expedients founded on rough trial and error and incomplete and inadequate experimentation? Here is truly a test of how intelligently these long-range problems of resourc use and development can be met by agencies of government. Or must we depend on privately endowed institutions or foundations to give the necessary long-range attack upon such basic problems that determine the destiny of a nation?

There is obviously a need for realization on the part of those who formulate long-range policy of the country, including government and private enterprise, of these basic problems that condition and determine the productive capacity of the land base of the country.

The Research Committee on Land Erosion, therefore, brings to the attention of the American Geophysical Union its finding that: Research into the basic problems of erosion are lagging to the detriment of a long-range land and water policy of the country; and solemnly recommends:

(1) All interested agencies, governmental and private, be called on to give special attention to the deplorable state of research in erosion, in its dynamics and in its broad phases, as they affect not only the short-range but long-range view.

(2) There be called a series of field symposia of specialists of all interested fields of inquiry to evaluate the present status of our knowledge of erosional processes, and of means of possible control or retardation; and recommend to the Congress and to State governments and to private institutions a national program of research in erosion and its control, both as to what is presently feasible and ultimately desirable in the full use and conservation of the land base of the United States.

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REPORT OF THE COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1948-1949

H. G. Wilm, Chairman

Marvin D. Hoover
Joseph Kittredge
Harold J. Lutz
B. G. Holzman
Luna B. Leopold
Harold C. Troxell
E. G. Dunford
A. H. Hendrickson
Adolph F. Meyer

Following the usual procedure of this Committee, a general topic was selected for discussion by the members, with the thought that they might deal with either methods of study or research results. Of the responses, two are presented in condensed form because they are expected to appear in full elsewhere.

Estimates of evapotranspiration losses

E. G. Dunford (Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado)--Soil moisture deficits induced by evaporation and transpiration in young lodgepole pine are currently being measured by B. C. Goodell at the Fraser Experimental Forest. The work is one phase of a study to determine how water available for streamflow is affected by thinning of typical second-growth stands growing in the Continental Divide zone of Colorado. Soil moisture is an important aspect of this investigation because autumn deficits must be satisfied before spring snow melt can contribute to streamflow.

Observations are made on a series of eighteen three-quarter acre plots. These are arranged by groups of three into six blocks which are located so as to sample as fully as possible the range of variation in soil, exposure, aspect, and stand density encountered in the general study area. In each block the following three treatments are repeated:

(1) Crop tree thinning, in which the most promising trees, at the rate of 100 per acre and spaced uniformly, are selected and released by removing all competition within a radius of eight feet. This leaves dense intervening fringes of trees untouched by the clearing.

(2) Single tree thinning, in which the best trees were selected at the rate of 625 evenly spaced individuals per acre and the remainder cut. This system resulted in more actual tree crown removal than the crop tree method.

(3) Check, in which the original, unthinned, second-growth stand remained.

The soil on all plots is of alluvial origin and relatively deep. Moisture samples are taken with a soil tube to depths of 48 inches and are separated into two parts at the 18-inch level. Spring measurements to determine field capacity are taken immediately after the snow has melted. These are followed by a second set at the end of the growing season in September, and deficits are determined by subtraction. The results are expressed in inches of water.

Preliminary observations based on the records so far obtained in two years are interesting indications of the final results:

(1) Soil moisture deficits have been reduced in significant amounts by thinning, regardless of the method. The single tree method shows smaller deficits than the crop tree method, as would be expected because of the greater crown removal; but the difference between the two methods has so far not proven greater than could be expected by chance.

(2) The effect of thinning is found to reach into the soil profile below 18 inches, indicating that transpiration, at least, exerts important effects in the zone between 18 and 48 inches. In order to arrive at the total effect of thinning on soil moisture deficits for young lodgepole pine, it has been concluded that samples must be taken to four-foot depths unless bedrock or impervious layers are encountered at shallower depths.

B. G. Holzman (Headquarters U. S. Air Force, Washington, D. C.)--Recently O. G. Sutton, Head of Mathematical Physics at the Military College of Science, Shrivenham, England, gave a series of lectures at the United States Weather Bureau on the problems of atmospheric diffusion. Among the lectures presented was a survey of the evaporation researches being conducted in England. Many fi pieces of work have been completed there and are in the process of being published. Sutton indicate that there was an increasing wealth of evidence that the wind shear and humidity gradient techniques were the most promising for the measurement of moisture losses from natural land areas.

J. Kittredge (University of California School of Forestry, Berkeley, California)--Transpiration and evapotranspiration losses have been determined from phytometers, tanks, and lysimeters either directly by applying the measured losses to areas of similar vegetation or by computing the transpiration ratio and applying it to the dry matter produced by similar vegetation growing under natural conditions. Many of the early estimates of transpiration in Europe and in the United States were bas upon the determinations of water losses per 100 grams of air-dry leaves of trees five to seven years old, grown in pots containing eight to 12 pounds of soil, by Von Hohnel in Austria about 1880.

Preliminary results from the San Dimas lysimeters during two years when grass (Bromus mollis) was growing in most of them provide some new and interesting evidence on the use of lysimeters to estimate evapotranspiration [COLMAN and HAMILTON, 1947]. These lysimeters are all close together on a level area and the soil for all of them was mixed and repacked with the greatest care, so that differences in climate or soil are negligible. Under these conditions the evapotranspiration losses from the same grass planted at the same time in the four sizes of lysimeters would be expected to be the same; and any observed differences in the losses must be attributed to the differenc in size or type of lysimeter. The dimensions of the lysimeters are given in Table 1. The large ones are made of concrete, the medium and small of galvanized iron, and the unconfined have no walls or bottom. The small lysimeters have no provision for the collection of surface runoff or percolation.

Table 1--Evapotranspiration from the San Dimas lysimeters of the California Forest and Range Experiment Station

Item	Season	Unconfined	Large	Medium	Small
Surface dimensions, ft	....	7.5 × 14.6	10.5 × 20.8	2.59 dia.	1.5 dia.
Depth, ft	....	6	6	3.17	2
Dry weight of soil, metric ton	....	26.7	62.2	0.73	0.14
Evaporation from bare soil, inch	1941	.....	.....	3.6	3.7
	1942	.....	.....	3.5	3.2
Evapotranspiration, inch	1941	9.0	5.6	4.9	4.2
	1942	2.4	4.3	3.6	3.3
Aver. oven-dry yield of grass, metric tons/acre	1941	1.59	1.40	0.57	0.26
	1942	0.51	0.51	0.18	0.18
Evapotranspiration ratio	1941	590	423	881	1700
	1942	480	859	2095	1933.

The evaporation from bare soil for the medium and small lysimeters and for all four sizes, the evapotranspiration from the grass-covered lysimeters, the yields of grass and the ratios of evapotranspiration to yields of grass are given in Table 1 for the seasons of April to October, 1941 and 1942. Precipitation in the rainy season of 1940-1941 was 48 inches and in 1941-1942, 16 inches. Evaporation from bare soil in the small tanks was 0.1 inch more in 1941 and 0.3 inch less in 1942 than in the medium lysimeters. Comparisons for three earlier seasons showed equality or small excesses for the medium size.

Evapotranspiration decreased with the size of lysimeter from large to small, with higher values in the wet year than in the dry year. If it is assumed that the unconfined lysimeters represent the closest approach to natural conditions, then in the wet year, estimates derived from the large, medium, and small types, would be 38, 46, and 53 per cent too low. Just the reverse is true in the dry year, when the corresponding estimates would be 79, 50, and 38 per cent too high. The evapotranspiration losses from the lysimeters of whatever size could not be applied safely to natural area

Evapotranspiration losses in the dry year are only 0.1 inch greater than evaporation from bare soil. In the wet year, they are 1.3 inches higher in the medium and 0.5 inch higher in the small lysimeters.

The yields of grass reflect the differences in the lysimeters much more than do the losses of water. In 1941, if the yield of the unconfined is taken as 100, the percentage relatives are 88, 36, and 16 for the large, medium, and small respectively. The yields are lower in the dry than in the wet year and in the dry year the differences between unconfined and large and between medium and small disappear.

The weights of water lost by evapotranspiration per unit dry weight of grass produced are generally larger in both seasons in the smaller lysimeters. If these ratios were applied to yields of the grass on other areas presumably corresponding to those in the unconfined lysimeters, the estimated losses derived from the large lysimeter would be too low by 28 per cent, and too high from the medium and small by 49 per cent and 188 per cent on the basis of 1941 figures. For 1942, the estimates would be too high by 79 per cent from the large, by 336 per cent from the medium, and by 303 per cent from the small lysimeters. By this method also it is obvious that estimates of evapotranspiration losses derived from lysimeters or tanks or pots are likely to be unreliable for application to areas of the same soil and natural vegetation, and the smaller the containers, the less reliable they are likely to be.

Luna B. Leopold (Pineapple Research Institute, Honolulu, Hawaii)--To the casual observer, Hawaii gives the impression of being well vegetated in the lowlands as well as the mountains. Conspicuous erosion (recent) is confined to Molokai, Lanai, and Kahoolawe, small islands having a large proportion of their areas at low elevation.

Rainfall varies enormously through short, horizontal distances. It occurs as (1) orographic rain, controlled by the mountains and with sharp leeward-windward differences with respect to the persistent trade wind, and (2) general rains reflecting high-level disturbances in the westerlies aloft. The general rain patterns also show distinct influence of orography.

In the late part of the Nineteenth Century and early in the Twentieth, there was severe overgrazing by cattle, sheep, and goats. Superimposed on this influence was the continual importation of exotic species of plants, both purposeful and unintentional. In the past three decades there has been tree planting on a large scale aimed at conservation of water by retardation of surface runoff.

The present landscape reflects these influences. Practically all plant species in the moderate and low elevations (below the native rain forest) are exotic. Guava, haule koa (Leucaena glauca), kiawi (Prosopis) lantana (L. camara), and over large areas, cactus (Opuntia megacantha), dominate the flora of land not used for pineapple, sugar, or homesites. In the lower portion of the native forests, one grass, a Panicum (an exotic) is rampant. In the forest areas, the ground cover is to a large extent covered with four exotic species of fern, particularly Dicranopteris.

In certain areas, particularly southeast Maui and the Waimea-Kukuihaele area of Hawaii, there is evidence of a retreat or diminution of an original forest cover.

As in many other Pacific islands, the Ghyben-Herzberg groundwater lens is one of the most important sources of water for agricultural and domestic use. Honolulu, particularly, has one of the most perfectly developed examples of such a lens. In the area adjacent to and in Honolulu, there are indications that inroads into this supply should be viewed with alarm. This situation has recently been summarized by WENTWORTH [1947]. Transpiration and evaporation measurements were made on Oahu in connection with geologic and groundwater investigations, using grass as the vegetation cover [STEARNS and VAKSVIK, 1935]. Large variations between locations were found. Wentworth states that measurements made to date connot be accepted as even a rough sample of evapotranspiration quantities in the rugged topography and diverse forest cover and rainfall. He doubts whether an adequate sampling can ever be made.

There is a shortage of land in Hawaii for uses of all kinds, residential as well as agricultural. Therefore, there is continuous pressure on land administering agencies to open new lands to grazing, and to residential and business uses. The Board of Forestry and Agriculture and other agencies dealing with water have withstood such pressures very well, on the whole. In some cases they have argued that decrease of the forest cover would decrease rainfall. Such arguments are gradually being replaced by more tenable ones, but even now there is a tendency for both the forest protectors and those wishing to encroach on forest areas to cite inapplicable or outmoded evidence to support their respective views.

It is interesting that the large-scale tree plantings which have been made over many years have been for the purpose of water conservation. No experiments of any kind have been made to test the magnitude of evapotranspiration changes which might be expected with these various exotic tree species. It has been tacitly assumed that the tree planting program has a beneficial effect on the available water and on the watershed.

BRYAN [1947] summarized the tree planting work on the big island, Hawaii. In the 25-year period following 1921, approximately 9.7 million trees and about five tons of seeds were planted on that island. The survival of planted trees has been over 90 per cent. In the same period a total of 257,000 wild animals, mostly goats, sheep, and pigs, have been killed in roundups on the island of Hawaii.

The magnitude of the tree-planting operation, together with the large-scale establishment of exotic plant species reproducing naturally, would make it easy to believe that the total water loss by transpiration has increased since settlement. It probably will never be possible to evaluate this but considering the importance of the whole water problem it is somewhat surprising that the subject has not been made the object of more research. In respect to these circumstances, Hawaii is a good example of how a lack of over-all water policy cannot lead to optimum use of available resources.

Adolph F. Meyer (Consulting Engineer, Minneapolis, Minnesota)--A paper entitled Evapotranspiration from groundwater fluctuations, which presents the results of studies in Nebraska, is in preparation and will be published at a leter date in the Transactions.

Harold C. Troxell (U. S. Geological Survey, Los Angeles, California)--A paper by Harold C. Troxell and Harlowe M. Stafford, entitled Natural water losses in mountain drainage areas of Southern California appeared in the October 1949 issue of the Transaction, pages 752-758.

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Transactions, American Geophysical Union Volume 30, Number 6 December 1949

REPORT OF THE COMMITTEE ON SNOW, 1948-1949

R. C. Farrow, Chairman

1949	1950	1951
P. E. Church	J. E. Church	Wayne D. Criddle
R. W. Gerdel	R. N. Parshall	Forrest L. Rhodes
R. F. Legget	R. A. Work	V. J. Schaefer

Nomenclature and classification of snow

For some time past it has been evident that an attempt should be made to produce a nomenclature which would be widely acceptable. With the broadening interest in snow generally, among groups whose interests are more or less divergent, a certain amount of confusion has arisen. As far as this continent is concerned the Committee on Snow of the AGU appeared to be the logical body to undertake this task. Last year therefore the nucleus of a Sub-Committee on Nomenclature was struck with power to add. Before it had commenced functioning, however, we were advised that a committee was set up to work on a standard classification for snow arising out of the meeting of the Commission on Snow and Ice as part of the Eighth General Assembly of the International Union of Geodesy and Geophysics at Oslo in 1948. Our embryo sub-committee was therefore discontinued.

The international committee consists of G. J. Klein (Canada), V. J. Schaefer (U. S. A.) and Marcel de Quervain (Switzerland) with power to add. Schaefer had also been a member of our sub-committee. The cooperation of the Committee on Snow has been extended to the new international committee.

In this connection Schaefer writes that the committee set up by the International Commission on Snow and Ice is to attempt the development of an international classification of snow, both as falling snow and snow on the ground. Letters have been sent by the committee to workers in the field of snow studies requesting information on classification methods now in use. When these have been obtained, it is hoped that some compromise might be effected in extracting the basic facts common to all the methods and then work up a simple and practical classification system. An effort has been made to get into touch with the known workers in the field, although it is not certain that the lists are complete. It is the hope that it might be possible to obtain additional information from those not now on the lists. Three or four copies of suggested classification methods should be sent to V. J. Schaefer, in care of the General Electric Company, Schenectady, N. Y., or to G. J. Klein, National Research Council, Ottawa, Canada.

Laboratory studies in relation to the growth characteristics of snow are still actively underway in the General Electric Laboratory at Schenectady. The results of these studies will be published from time to time. A fairly extensive paper on Schaefer's laboratory studies of snow will soon be published in Chemical Reviews as part of the Aerosol Symposium held in Chicago.

The Oslo Meeting

This appears to have been an outstanding success from the standpoint of snow and ice on which over forty papers were presented. It was hoped that at least the titles of these would have been available for inclusion in this report; they were promised but are not yet in hand.

J. E. Church (Nevada Agricultural Experiment Station, Reno, Nevada) only returned from India and South America last year in time to leave for the meeting of the International Union of Geodesy and Geophysics at Oslo. His voluminous reports on snow surveys in the Himalayas and the Andes are still in the hands of translators but he supplies the following notes on his activities.

He spent five months in India and traveled on horseback 300 mi in the southeastern Himalaya. There the seasonal snow is found mostly above 14,000 ft, but in the northeastern Himalaya the snowline is much lower and more accessible. Glaciers provide only a relatively small portion of the run-off late in the season. The monsoons occur in summer and fall mainly below 8000 ft. The seasonal snow provides early water but a minor flow as compared with that produced by the monsoons.

In the Andes of southern South America a snow survey system was provided for approximately 40 basins, extending 2000 mi or more southward into Tierra del Fuego. The northern portion is bare, steep, and windswept. The snow cover is scant but sufficient to sustain a population of 300,000 at its eastern base. The southern portion has an annual precipitation of 60 to 120 inches of water and has heavy forests and regulating lakes. The snow-melt runoff, aided by altitude and lakes, continues from five to seven months.

A reconnaissance flight along the crest was made in search of snow-survey courses. Glaciers were numerous and extensive but appeared only occasionally as ice-cliffs from their covering of seasonal snow. Only when the snow has melted can the Sun gain access to the ice. Only in the south are the glaciers active. In the north they are static and are slowly evaporating into the forms of the "nieve penitente," or pinnacles.

In the Alps, which he visited after the meeting at Oslo, the Swiss feeders of the Rhine and the main Rhine at Basel and the Rhone at Geneva were found harmonious in their snow-melt flow within approximately 15 per cent based on their normals. A snow-survey system on the Rhine near its source would be sufficient for the others. The total area of Switzerland, he comments, extends about 100 by 150 miles.

He suggested international snow-surveys in all three mountain ranges after the manner of the surveys in the United States and Canada; for the Himalaya by India, Nepal, and Pakistan; for the Andes by Argentina and Chile; for the Alps by Switzerland, Netherlands in its Zuyder Zee Reclamation Project, and France. Such international cooperation, he believes, is not only essential for accuracy and economy but will become a bond of peace.

Shielded snow gages

C. C. Warnick (Engineering Experiment Station, University of Idaho)--The project, Wind studies on shielded snow gages, known as Special Research Project No. 17, was started in June, 1948, and came about as the result of suggestions from representatives of Region 1 of the United States Bureau of Reclamation. The Weather Bureau, Soil Conservation Service, Corps of Engineers, Forest Service, Civil Aeronautics Administration, all of the Federal Government, and Washington Water Power Company have been cooperating in this endeavor.

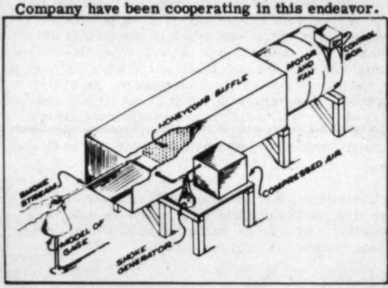

Fig. 1--Schematic drawing, showing smoke wind tunnel used in studies of high altitude precipitation gages

The project has been approached in two ways. First, a laboratory investigation has been started on the study of air movement around precipatation gages with various shapes of shields. This laboratory study was conducted by using a smoke-wind tunnel. A model of the gage and shield were placed in front of a jet of white smoke to observe and to photograph the airflow phenomena around the gage orifice. With 1/4-scale models it is questionable as to just how to interpret results. Figure 1 gives a schematic diagram of the setup used.

The second phase of the project has entailed the installation of a number of experimental storage precipitation gages at a mountain location near Mullan Pass, Idaho. The site is in a clearing of lodge pole pine trees at an elevation of approximately 6000 ft. This battery of gages is being observed by representatives of Civil Aeronautics Administration stationed nearby at an aircraft communication station. Special shields have been adopted for experimentation as a result of indications found in the wind studies. Five gages have been in operation since October, 1948.

Much future work must be done to find out more about relative performance of various shields. Additional wind studies will be made during the summer of 1949. Improvements and additions will be made at the field installation in an attempt to determine actual operating characteristics of the gages and shields.

Interception of snow by tree crowns

Joseph Kittredge, (School of Forestry, University of California, Berkeley, California)--Analysis of the data on the interception of snow by the crowns of trees from different types and densities of forests on the Stanislaus National Forest at elevations between 5000 and 6300 ft, indicates that the interception expressed in inches water equivalent gives a linear regression with the water equivalent of the precipitation which, in almost every case, is highly significant statistically. Expressed as an equation, $I = bP + a$, where P is the precipitation per storm, b is the proportion of the precipitation intercepted, and a is approximately the interception storage capacity of the crowns. In general, there is a wider variation in the values of b and a within the same stands, depending on the positions of the gages with reference to stems and openings, than there is between different types of forests. The regression coefficients in the larger openings between the trees usually have negative values, at one station as low as -0.19 inch, which, of course, means that the accumulation of snow in the openings is greater than at the control stations in a large clear area. Under the crowns the regression coefficients may be as high as 0.40 at individual stations. The values for interception storage are, in general, higher than those that have been reported for rain, in one case being as high as 0.31 inch. Averages for several stations in the same stands range from 0.06 to 0.19 inch. Considering the way in which wet snow accumulates on the crowns of trees, it is not surprising that the interception storage is higher than for rain.

Cooperative snow investigations

Forrest L. Rhodes and R. W. Gerdel (Cooperative Snow Investigations, Oakland, California)--During the year to April, 1949, the three snow laboratories operated jointly by the Corps of Engineers and the United States Weather Bureau have continued to collect a large amount of hydrologic and meteorological data. The three laboratories being operated under this program will carry on the same general observational program as originally outlined in previous reports. There have not been any major changes contemplated in the general program.

Particular emphasis has been placed upon the development of instruments and techniques for the measurement of water transmission rates through snow. Additional ground water wells have been completed in several of the laboratories and a small basin-lysimeter constructed at one laboratory. Research is being conducted on the use of certain radioactive materials as indicators for the measurement of the water equivalent of the snow on the ground. The pulse from the radioisotopes has been successfully telemetered to a strip chart recorder and the rate of snowmelt measured without disturbance of the snowpack. Progress is being made on the adaptation of a radio-telemetering system to the radioisotope snow stake. Expansion of studies on longwave radiation exchange have been undertaken and new radiometers have been obtained for this purpose.

The preparation of analytical reports has continued, with emphasis on summaries of basic data. While it is rather early in the program to offer general conclusions, it is noteworthy that the magnitude of nearly all the hydrologic and meteorological elements observed has been extremely variable over very small distances, indicating the great importance of terrain parameters in the areal distribution of these elements.

Solar radiation

George A. Crabb, Jr. (Soil Conservation Service, East Lansing, Michigan)--This project is under the joint auspices of the Soil Conservation Service of the United States Department of Agriculture, and the Michigan Agricultural Experiment Station and is conducting a research project towards relating solar radiation with the problems of snow-melt, evaporation, and soil moisture. Seven years of record are now available and Crabb states they have evaluated the pattern of solar radiation on a day-to-day basis for East Lansing. Papers covering the project are in course of preparation.

Snow surveys

Federal-State Cooperative Snow Surveys have materially expanded their network in Colorado and Wyoming.

Several new courses were added to the British Columbia network last year, for the Columbia Basin. In addition, a long planned start, accelerated by public demand arising out of last year's disastrous floods, is to be made this year on a snow survey network for the Fraser River Basin.

Snow surveys were never designed for flood forecasting, nor can they be expected to indicate anything but a potential, but last year in the Pacific Northwest they performed a valuable service in pointing out the extreme flood hazard which existed. The data available to snow surveyors and runoff forecasters by May 1, 1948, so clearly indicated almost inevitable floods, that independent warnings were issued by both British Columbia and U. S. Federal-State snow-survey authorities.

As a result of the experience in 1948, a number of high-altitude key snow courses are going to be sampled each year as of May 15 and June 1 in order to provide an index to the shrinkage rate of the snow pack in response to melting, and therefore the remaining potential runoff. This is planned for the Columbia Basin both in Canada and the United States. In addition periodical aerial surveys are planned experimentally for some British Columbia watersheds.

The Western Snow Conference met with the Colorado River Water Forecast Committee, April 15-17, 1948, at Reno Nevada, with a full program of technical papers. A highlight was the presentation by the Conference of a medal to J. E. Church in recognition of his outstanding achievements in the study of snow.

The Eastern Snow Conference held a highly successful meeting at Greenfield, Massachusetts, on February 10 and 11, 1949.

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REPORT OF THE COMMITTEE ON RUNOFF, 1948-1949

C. C. McDonald, Chairman

W. C. Ackerman
W. M. Berry
C. O. Clark
H. L. Cook
R. W. Davenport
W. U. Garstka
Gail Hathaway
G. R. Williams
W. T. Wilson

Because of the widely scattered locations of the membership, no assembled meeting of the Committee was held during the year, all discussions being held by correspondence. Consideration was given to three subjects during the year: (1) standardization of terminology as related to runoff (continued from previous year), (2) deficiencies in hydrologic research, and (3) current programs of hydrologic research.

Terminology--With respect to terminology, the wide divergence of opinion among committee members with respect to the definition of terms fairly common in hydrologic literature emphasizes the need for more uniformity. Various authors use the same terms to describe slightly different runoff phenomena. The Committee, while unable to agree at this date on recommended definitions, urges writers to restrict their terminology so far as practicable to that previously used. Nothing is gained by inventing a new name for a phenomenon which has already been satisfactorily named by a previous writer. On the other hand, precise definitions are necessary to proper understanding, and loose usage of runoff terms only destroys their usefulness. Where any question as to the intended definition exists, it is preferable for the author to present his definition until better agreement as to the accepted definition has been reached.

W. T. Wilson comments that it is difficult, from a semantic standpoint, to be very optimistic about the prospects of a committee, by correspondence, to accomplish much in a few years. No matter what words are used in the definitions of an element or concept, the definition is actually performed by the natural or analytical process which determine the element or concept. For example, it is stream measurements that define rating curves. In considering the components of runoff: overland flow, effluent from ground water, infiltration, and others, it is instructive to employ what P. W. Bridgman terms the operational type of definition. As the name suggests, the operational definition describes the operations necessary to obtain the element or concept under consideration.

An operational definition describes a process, just as a legal definition of a plot of ground describes a process, for example, metes and bounds. This method requires a firm factual basis, not the recitation of a few examples illustrating some high-order abstraction originating in a person's mind. The term basin-wide infiltration, for example, is meaningless unless the observations and operations necessary to define it are described. As long as people try to observe and compute infiltration by a great variety of methods, it is difficult to see how agreement can be reached on a specific definition. There are probably as many different definitions of infiltration as there are people trying to determine it. It seems doubtful if hydrologic terms can be satisfactorily standardized until there is better understanding and more agreement regarding the natural processes involved.

C. O. Clark says in part that we can do a useful job in standardizing a few definitions and terms, but I think we should go very slowly in defining the terms beyond the present state of agreement, or in the direction of some personally held concept. Thus to take the term unit hydrograph, for example, we can agree that it is a mathematical expression of the chronological sequence of observed stream flow following a specified sequence of rainfall or runoff. But when Sherman said in his definition that it was "surface" runoff he was using a meaningless, indeterminate word which unnecessarily restricts the use of the technique and implies an impossible distinction between surface and subsurface flow. And the distinction in unit graphs and distribution graphs, fondly followed by some writers, is a meaningless controversy over dimensions, between the complex dimension of cfs per inch times watershed area versus the simple dimension of per cent per unit of time. Both units simplify to the reciprocal of time. He comments that he derives all unit graphs as distribution graphs and converts them to unit graphs, finds them equally useful, but find the former more useful when working alternately in metric and English units. He prefers the term unit hydrograph.

W. C. Ackerman is a member of the group on Unit Hydrograph Data of the subcommittee on hydrologic data of the Federal Inter-Agency River Basin Committee which attempted to standardize the compilation of data for the unit hydrograph. Because the objective of this group was toward standardization, he has summarized its recommendations as follows.

In April 1948 the Government agencies represented on the Subcommittee on Hydrologic Data of the Federal Inter-Agency River Basin Committee completed a bulletin on Instructions for Compilation of Unit Hydrograph Data. Primarily this consisted of two basic data forms for preparation of individual unit hydrographs and also contained a pertinent data form for summarizing the results of unit hydrographs at a particular station. It is intended that these forms be used by the agencies represented for interchange of data and also to bring together on standard forms the mass of unit hydrograph data already prepared and continuing to be developed.

The forms, procedures, and definitions set forth in this bulletin are believed to be an important contribution to the further development of the unit hydrograph. Standardization was carried as far as possible considering the details of various procedures which have been in use and also considering the numerous uses to which unit hydrographs are put. The term unit hydrograph was agreed upon in preference to unit graph and other expressions which have been in use.

The basic forms and the summary pertinent data form each contain over 30 items which it was felt were important to develop the unit hydrograph characteristics. These items which are individually defined in the bulletin located the area to which the unit hydrograph applied, defined the watershed physical characteristics and the type of stream-flow records, provided for designation of the type of flow separation used in development, meteorologic and hydrologic characteristics of the observed storms, and the characteristics and coefficients useful in the Snyder synthetic unit hydrograph.

Deficiencies in hydrologic research--No comprehensive study of deficiencies in hydrologic research has been prepared by the Committee, but brief discussions by Committee members will be of interest.

G. R. Williams comments that one of the greatest needs is for data on unit hydrographs for small drainage areas (less than five square miles) in order to replace the use of the rational formula. Also runoff records for small areas are needed in order that frequencies of runoff volume and peak discharge may be developed for use in the design of culverts, bridges, and drainage works.

C. F. Izzard lists the following deficiencies in hydrologic research: (1) Continuous records of stream flow and rainfall on drainage areas under 100 sq mi are needed for practically the entire United States. (2) Existing data on stream flow and rainfall on small drainage areas should be analyz to determine magnitude and frequency of rates of runoff. (3) In studying data on peak rates of runoff on small drainage areas, we should endeavor to correlate these data with measurable characteristics of the drainage areas in each physiographic region. The Soil Conservation Service has recently published for their own use a number of bulletins applicable to limited regions of the country. This kind of research is valuable and should be encouraged. (4) Studies by Cross in Ohio and by others of magnitude and frequency of peak rates of runoff on streams within a given major watershed indicate the possibility of developing runoff charts applicable to an entire river basin having reasonably uniform runoff characteristics.

W. T. Wilson's comments deal with the most basic concepts of hydrologic investigations, and says that in addition to the subject-matter deficiencies there are technique deficiencies. Many of these are semantic: failure to distinguish properly between observation and interpretation, and starting out with a theory and proceeding too much be deduction instead of accepting the natural order of abstraction of observing stubborn facts and inducing relations from them.

In addition to this, there seems to be too little use of the statistical technique of identifying a dependent variable and expressing it as a functional relation according to the observed structure and operations of its related variables. There is still much dabbling with an imaginary hydrologic cycle, and speculation on absolute magnitudes of basin-wide elements, of which adequate samples are unavailable, and whose values may never be known. A candid acceptance of this important fact might lead to more productive work.

Possibly one of the greatest deficiencies is our slavery to the traditional method of analysing a hydrograph, in which we estimate infiltration, correct for base flow, adjust precipitation records, assess temporary storage, assume this and that, and classify the residual as evapotranspiration. With expedient juggling and the use of appropriate "answer-factors" plausible results are obtained. We pretend to balance our books without having the necessary records. There is seldom a unique solution, yet we see paper after paper and report after report in which solutions are presented. Many of these products are exercises in ingenuity, in which the results are derived more from the writers' assumptions and notions, than from the relations and structures and operations observed to exist in nature.

Research on runoff--A brief review of the research activities of the organizations represented by Committee members follows.

C. O. Clark (consultant to the Venezuelan Government) comments that in the hydrologic activities of the Venezuelan government, are the institution of classes in hydrology in the curriculum of the University of Caracas, the National University; and in applied hydrology in the Ministry of Public Works, Irrigation Division (Ministerio de Obras Publicas, Direccion de Obras de Riego). In the latter class on investigations are work on the unit hydrograph, general relation between rainfall and runoff, and studies of rainfall to determine reasonable criteria for intense rainfall over watershed areas. In a country where a hydrologic record of five years is long, much field measurement must be done by people with equivalent of only two years of high school education, and where Latin courtesy encourages people to tell what the listener would like to hear regardless of its connection with scientific observation, some of these studies are of a crudity which will hardly appear scientific to other committee members.

In the unit hydrograph field, which is new in hydrologic work in Venezuela, use is made of the method and theory of approach which Clark suggested in 1945 in the Transactions [p. 1484] of American Society of Civil Engineers, working toward a correlation of velocity of concentration or channel storage capacity in hours per mile, a reciprocal of velocity, with slope of the channels involved. Venezuelan streams are very steep and data for a few streams with slopes above 200 ft/mi and velocities of concentration of 15 mi/hr have been encountered. These data compare well with the data given in the 1945 paper, considering the much steeper slopes. Accurate work is further handicapped by the fact that streams of this velocity rise and fall in two to three hours, and it is difficult to establish time of rainfall and stream rise accurately within this period of time. Furthermore, in a tropical climate, most rain is in thunderstorms of erratic distribution and little correlation between the rainfall which occurs on a watershed and that which is observed at a few precipitation stations. So the theoretical background for unit hydrographs, namely, uniform rainfall or runoff, does not actually exist.

G. A. Hathaway of the Corps of Engineers, reports the continuation of several projects in progress last year, such as the cooperative snow investigations, airfield drainage, mole drainage, arctic drainage, and electrical drainage. In addition to the above, and to routine investigations of runoff necessary to preparation of reports and to planning and operation of flood-control and navigation projects, the Corps is making an analysis of unit hydrograph data now available. The objectives of this study are to evaluate the accuracy and limitations of unit hydrograph methods to supplement available data as required for adequate coverage of basin sizes and runoff characteristics, to verify existing methods of estimating synthetic unit hydrographs, derive appropriate coefficients for their use, and improve methods. The studies are being conducted by the Washington District under the general supervision of the Office of the Chief on Engineers.

Upon completion of the initial phase of the unit hydrograph studies it is anticipated that the Washington District will begin preparation of generalized charts and tables showing flood runoff volumes for various durations and average frequency of various volumes in representative drainage basins in the United States.

W. T. Wilson of the United States Weather Bureau reports that during the year, Weather Bureau River Forecast Centers at Kansas City, Missouri, and Cincinnati, Ohio, began forecasting operations for their respective areas. Water Supply Forecast Bulletins for the western states were issued from new Water Supply Forecast Centers established at Salt Lake City, Utah, and Portland, Oregon.

The Bureau continued an active program of research in river forecasting techniques. Minor refinements were introduced into the techniques used in forecasting the runoff from rainfall, and exploratory work was initiated to develop techniques for forecasting the runoff from melting snow in mountainous regions. A pilot model of a new electronic flood routing machine was assembled and subjected to exhaustive tests. It has been shown conclusively that this machine can perform usual flood-routing operations for natural rivers more accurately and far more quickly than has been possible with manual methods. In addition, the machine can be used for routing runoff from rainfall to determine the outflow hydrograph of small basins.

The participation of the Weather Bureau with the Corps of Engineers in the Cooperative Snow

Investigations has continued.

W. C. Ackerman of the Tennessee Valley Authority reports that in the course of planning, designing, constructing, and operating nearly 30 large multiple-purpose projects the Tennessee Valley Authority is concerned with runoff in many phases of its engineering work. Other phases of TVA's activities such as the agricultural program, malaria control, navigation, and others are also directly concerned with runoff.

Basic to all runoff investigations is the network of approximately 350 stream gages used to measure the runoff along the Tennessee River and its tributaries ranging from major streams to small experimental watersheds. Records collected are primarily of the recording type and 21 of these have radio transmission.

In addition to the continuous and routine measurements of runoff at regularly established gaging stations all unusual current and historic floods are investigated and reported upon. During the past year these have ranged from the large-area storm of February 1948 which set record discharges on major subdivisions of the Tennessee River to small-area floods resulting from cloudburst rains.

In connection with the forecasting of river flows for the operation of TVA dams considerable attention is continuing to be given to the improvement of methods of stream-flow forecasting. Improvements under study include new approaches to the estimating of storm runoff, measurement of reservoir profile storage, and improved unit hydrograph and reservoir routing methods.

In operation of the reservoirs increasing use has been made of extended stream-flow forecasts based on the supplies of ground water. Monthly analyses of ground-water reserves are made by hydrograph analysis using the recession curve approach.

Recent studies in the Hydraulic Laboratory of the Authority's Hydraulic Data Branch have been highly varied. This report does not attempt to describe adequately these or list them in detail, but in most instances only indicates the type of investigations being carried on. These have included spillway and spillway apron model studies checked by field measurement, tunnel and outlet structure design model tests, experimental cavitation studies, surge tank model studies, bed load model studies, and field measurement of sluiceway discharges. During the past year a scale model was used to calibrate a modified Columbus deep-notch weir under various approach conditions in connection with investigations being carried on on a small experimental watershed. Another development of interest in the field of runoff was an experimental study to design and test a continuous silt sampling device which collects a 1/100,000 part of any discharge ranging between approximately one and 250 cfs. Recently considerable attention has been given by the Hydraulic Laboratory staff to field measurements of turbine discharges aimed at increasing the accuracy in reported discharges for the proper operation of the Authority's unified system. For tributary dams discharges are determined by means of current meter measurements downstream from the respective dams. On the main river where tailwater river stages are not easily stabilized, discharges are to be determined for individual turbines by obtaining velocity traverses in the turbine intakes.

A study is being continued to determine the roughness coefficients in several river reaches of known discharge to extend knowledge in the field between the roughness coefficient and physical characteristics of river channels.

Water travel in natural streams and through large reservoirs has been studied in connection with sanitation and siltation studies using electrical conductivity and chemical concentration methods for identifying masses of water.

An active program of research in runoff and other factors as related to land use and land treatment methods has been continued by the Authority, some of which studies are carried out in cooperation with other agencies. Areas under investigation vary from a few acres in size to over 100 sq mi depending upon the factors being investigated.

C. F. Izzard of the Public Roads Administration reports that the Public Roads Administration at the present time is concentrating its efforts on promoting use of existing data on stream flow by design engineers in the State highway departments. The first step in this program necessarily involves training of their personnel and State highway department personnel in the application of hydraulics to flow of water through culverts, bridges, and open channels. Concurrently the training program also includes instruction in how to estimate the magnitude and frequency of flood flows where stream-flow data are available and to suggest how such data may be expanded to give some indication of rates of runoff which may be expected on streams for which there are no continuous records. We are attempting to make use of all of the basic data available from the Geological Survey and from the Soil Conservation Service or other Federal agencies collecting data on stream flow.

R. W. Davenport of the United States Geological Survey reports that during the year the Geological Survey has made progress in the investigation of roughness coefficients of natural channels by the computation of values of "n" from information obtained by detailed instrumental surveys of reaches of streams through which the discharge is known by current meter measurements. During 1948 about 30 determinations were made for discharges ranging from about 150 to about 1,000,000 cfs with values of n ranging from about 0.019 to about 0.070.

The Geological Survey has also started during the year a program for the determination of the relative merits of the mean-section and the mid-section methods of computing the discharge of a current meter measuration in respect to (1) accuracy of the computed value of discharge; and, (2) amount of time required for the computation of discharge.

Hydrologic units have been set up in New York and Washington to report on floods as soon after they occur as practicable. Flood-frequency compilations and studies are underway in Maine, Massachusetts, Connecticut, New Jersey, Minnesota, Washington, and Missouri.

An investigation of (1) the water used, (2) the quantity needed, and (3) the quantity available for rice irrigation in southwestern Louisiana was begun late in 1948 in cooperation with the Louisiana State Department of Public Works. A field study of the variation in peak discharge with drainage areas below 25 sq mi was begun in the summer of 1948. Crest-stage gages have been installed at five sites on streams draining from 0.5 to 13.5 sq mi in the area above the gaging station on northwest Branch Anacostia River near Colesville, Maryland (21.3 sq mi). Two recording and five nonrecording rain gages are being maintained in the study area.

Water-Supply Paper 1080, Floods of May-June 1948 in Columbia River Basin was published during the year. It contains a section on magnitude and frequency of floods in the basin.

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TECHNICAL NOTE

RECENT DEVELOPMENTS IN CURRENT-METER DESIGN

Steponas Kolupaila

It is now some 50 to 70 years since the classical works of European and American investigators developed the present techniques of measuring the discharge of rivers. Since then, hydrometric instruments have been improved a great deal, although there have been no essential changes or advance in the basic methods of hydrometry. Modern needs require research in two new directions, as follows:

(1) Research into the hydrology of remote, inaccessible and uninhabited regions such as deserts, mountains, tropical forests, and glaciers which will require convenient and portable equipment, universal in application, resistant to cold, ice, heat, and debris. Automatic registration and transmission, simplified methods of measuring, and convenient ways of computing are especially to be desired.

(2) Measuring of water discharge over weirs and in canals and pipes, especially while testing turbines and pumps, must be completed very precisely (within 0.5 per cent) and quickly, so that the controlled water discharge does not change during measurement. Various new methods have been proposed and tried, such as the salt dilution, salt velocity, contracted opening, and Gibson methods; nevertheless, they have not displaced the old and merited current meter.

Current meter--The two types of current meter were independently developed: the cup type with conical cups turning around a vertical axis, introduced by W. G. Price in 1882, now almost exclusively used in America, and the screw type with blades rotating about a horizontal axis, invented by R. Woltman in 1795 in Germany, now in common use in Europe, Asia, and Africa. In turbulent flow the cup type tends to over-register and the screw type to under-register. In angular currents the cup type cannot measure the projections of velocities and is therefore not satisfactory. The continuous use of this type in America can be justified only by its expert manufacture.

Generally the water discharge of a stream is measured with one current meter by placing it successively in many points of a cross section or by integrating mechanically along horizontal or vertical lines in the section. At present, efforts are made to employ many current meters simultaneously, sometimes 25 or more. Determination of water discharge is more convenient when the runners of all instruments employed are uniform. Up to the present that was attained in the cup type with an exactitude almost sufficient for common use. Such a runner of the screw type has now also been developed.

A new current meter--Recent improvements of current meters of screw type in Germany (A. Ott, Kempten) meet the following specifications:

(1) The form and size of the instrument is such as never to interfere with its operation; the rating curve remains the same for every method of suspension (weights, rods or wires).

(2) Axis, ball bearings, and electric contacts are protected against water, sand, and mud.

(3) The instrument is easily taken apart for checking or cleaning, and simply put together without screw driver.

(4) Electric leads and connections are made as simple as possible, yet secure.

Significance of the component runner--A very important factor is the form of the runner. The early opinion that any runner measures the projection of angular current $V \cos a$ has not proved true. A regularly milled runner of a screw form measures the projection $V \cos^{n} a$. The so-called component runner, which would measure the true projection $V \cos a$, was an old reverie of hydrographers. The efforts up to recent times to achieve one brought no success. In 1948 the secret of the component runner was discovered by A. Ott, Kempten; such a runner will be manufactured in a short time, after the patent formalities are completed. Figure 1 shows the characteristic of a component runner in angular rating, in comparison with a normal runner, which measures the projection $V \cos^{1.5} a$ between ± 40°.

The component runner is advantageous under the following conditions:

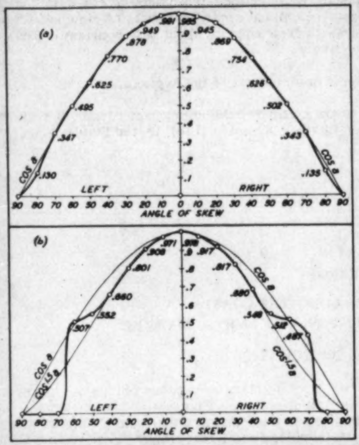

Fig. 1--Deviation of registrations with current meter askew to direction of motion, (a) Ott meter with component runner No.144k; (b) Ott meter with normal runner No. 146

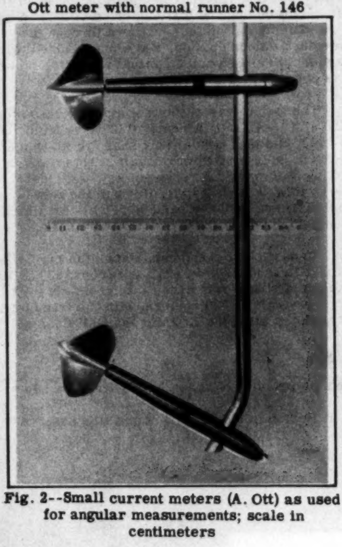

Fig. 2--Small current meters (A. Ott) as used for angular measurements; scale in centimeters

(1) In oblique currents, even as great as ± 60° declination from the normal (it measures the projection of velocity on the perpendicular to the cross section).

(2) For integrating the velocities along a vertical or a horizontal line (the component of the velocities of the meter and of the water is oblique, and a more rapid integration is possible with the component runner).

(3) Near the bottom of a canal or the wall of a pipe, where the velocity gradient is rather large (the opposite blades of the runner are exposed to different magnitudes of actions; thus there appear circumstances similar to an angular current).

(4) If the water velocity pulsates in magnitude and in direction (the component runner alone can be efficient in integrating a pulsating stream).

Problem of angular flow--Great difficulties are met when current meters are employed at water-power plants of low head. The only possible measuring section is in a canal near a weir or a gate, or at the inlet of the spiral casing to the turbine, where the water currents are non-uniform and oblique. Special temporary arrangements for improving the direction of current are very complicated and, moreover, can change the normal conditions for turbine operation. In this case the axis of the instrument must be pointed exactly into the stream direction as measured, and the projections of the measured velocity must be computed on the perpendicular to the measuring profile.

At present there are two new ways available: (1) application of a component runner; (2) in absence of such a runner, measuring two components of velocity with an ordinary screw-type current meter, one of them with the meter normal to the measuring section and the other with the meter axis turned by a constant angle (say 30°). The current meter may be rated in advance in the oblique position. From the two measurements, the angle of the oblique current can be obtained rather exactly, and the needed projection of velocity can be computed.

Both methods were tested with success by the author in 1948 in the hydraulic laboratory in Töging, Germany. The small current meters of very careful construction (see Fig. 2) measured the velocities in the artificially distorted stream created by a gate inclined at 45 degrees in a very unfavorable cross section. The velocities were measured at 30 points and the discharge was computed by two graphical methods (by vertical and horizontal planimetering). For comparison discharge was measured with the same instrument in 15 points of another contracted section, where velocities were distributed very uniformly. All measurements were repeated with the common runner; in the angular stream the instrument was located twice at every point; namely, horizontally and inclined 30 degrees upward.

The results of one of these experiments (in litres per second) were: (1) Component runner; discharge in oblique cross section 131.8, in contracted section 131.5. (2) Common runner; discharge in oblique cross section 130.6, in contracted section 130.2. (3) Discharge over rectangular weir with free nappe, without side contraction, calculated by Rehbock formula, 130.1 and 130.5 respectively.

Differences between these results do not surpass one per cent of the average.

Further information concerning the new type of Ott meter and the component runner is available from the firm, A. Ott, Mathematisch-Mechanisches Institut, Kempten (13b), United States Zone, Germany.

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DISCUSSION OF

"SEA-LEVEL CHANGES ALONG THE COASTS OF THE UNITED STATES IN RECENT YEARS" by H. A. MARMER

[Trans., v. 30, pp. 201-204, 1949]

Henry W. Bigelow, Jr. (P.O. Box 2672, Cristobal, C. Z.)--Marmer's paper brings out the variability of the supposedly stable datum in a most interesting manner. Figure 1 shows the annual heights of mean sea level at Balboa (the Pacific entrance to the Panama Canal) and Cristobal (the Atlantic entrance) as determined by the Section of Meteorology and Hydrography, The Panama Canal. The dashed line curves associated with the two sea level traces were derived by working smoothed means according to the procedure set out by MARMER [1943 and 1944]. The height of sea level for the month of January for the period of record was plotted and a smooth curve drawn through the points. Smoothed values thus derived were tabulated for each month and smoothed annual sea level curve was obtained.

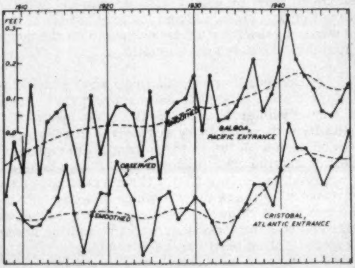

Fig. 1--Annual mean sea level at the Panama Canal

The Balboa curve shows a more or less steady rise at a mean rate of nearly 0.01 ft/yr from 1908 to 1942, and then a relatively sharp drop, which appears to be turning upward again. This trace does not seem to match the shape of any of the curves shown in Marmer's paper, although the rate of annual increase is of the same order as that which he found.

No particular trend can be found in the Cristobal data from 1909 to 1932, but from 1933 to 1943 there is a steady rise at the rate of nearly 0.02 ft/yr, a very close agreement with the trend found by Marmer along the Atlantic and Gulf Coasts.

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NOTES AND PERSONALIA

NOTES

Annotated bibliography of scientific literature relating to the region of the Gulf of Mexico--A publication, "Annotated bibliography of the Gulf of Mexico and contiguous areas" has been compiled by Richard A. Geyer and published by the Humble Oil and Refining Company, P. O. Box 2180, Houston 1, Texas. This is multilithed and contains about 50 pages, 8 1/2" × 11", covers various fields of science, including marine biology, oceanography, meteorology, geology, seismology, geodesy (gravity), and terrestrial magnetism. It includes items of long standing as well as those current. Interested persons should write to Mr. Geyer at the address given.

Scientific personnel sought by the Navy Department--The September, 1949, issue of the Scientific Personnel Bulletin lists many positions available to scientists and technologists, a goodly number bearing on various aspects of the broad field of geophysics. Interested persons should get into touch with the Civil Service Examiners in their region or write to the Office of Naval Research, Washington 25, D. C.

Symposium on air pollution investigation--The first National Air Pollution Symposium was held at the Huntington Hotel, Pasadena, California, November 10-11, 1949. Nineteen papers by authorities from all over the country were presented. The sponsors of the symposium were the Stanford Research Institute, California Institute of Technology, the University of California, and the University of Southern California.

New Scientific research center at Macao--The Zi-ka-wei Jesuit Observatory near Shanghai has been closed and E. Gherzi, its director, who had been engaged in scientific work in China for 32 years has been barred from returning to China after attending a Meteorological Congress in Manila. He has been temporarily engaged in Hong Kong, but has accepted an offer from the Portuguese Government to install a scientific research center at Macao. The center will make observations on cosmic rays and radar tropospheric echoes at the outset, and expand the program as facilities and opportunity provide. An appeal has been sent out for publications and other library material which may be sent to the Portuguese Embassy in Washington for expedition to Macao.

Isostatic reduction maps of Europe--The Isostatic Institute of Helsinki, Finland is preparing isostatic reduction maps based on the Hayford system, T = 113.7 km which they plan to complete this year. Maps for the Airy and Vening Meinesz systems will appear a little later.

Atlas of Denmark--The Royal Danish Geographical Society has published a new atlas of Denmark in five volumes, prepared by 25 scientists under the editorship of Niels Nielson. It contains about 800 maps and diagrams, mostly in color, with explanations in Danish and English. It is 38 × 55 cm in page size. The publisher is H. Hagerup, 10 Fiolstraede, Copenhagen, Denmark.

Western Snow Conference report--The Western Snow Conference has issued its Proceedings of the meeting held in Reno, Nevada in April 1948. It contains 16 papers with discussion as well as the other material related to the meeting. Purchasers should write to R. L. Parshall, General Chairman, Western Snow Conference, Fort Collins, Colorado.

Central Board of Geophysics established by Indian Government--In 1946, a Planning Committee for Geophysics was appointed by the Government of India to clarify ideas regarding the development of geophysics in India. Among the accepted recommendations made by the Committee was that a Standing

Committee for Coordination be established to (1) coordinate the existing resources of scientific departments and universities in geophysics for research, field work, and training of personnel; (2) develop the resources; and (3) set up a central Geophysical Institute. The new Committee has been designated as the Central Board of Geophysics, and has been appointed for a period of two years.

PERSONALIA

Dirk Brouwer of Yale University Observatory has been invited to attend the Colloquium on Astronomical Constants by the Paris Centre National de la Recherche Scientifique, to be held in Paris, March 27 to April 1, 1950.

A. B. Bryan, until recently Chief Geophysicist with the Carter Oil Company, has accepted a position with the Standard Oil Development Company as Assistant Manager of the Production Research Department with headquarters in New York.

E. E. Foster of the Bureau of Reclamation has been assigned to the Navy Department as consultant on hydrologic and hydraulic studies for the development of water supplies in Guam.

Jean H. Hawley, Assistant Director of the U. S. Coast and Geodetic Survey, retired from active duty on October 1, 1949. He was succeeded by K. T. Adams, formerly Chief of the Division of Photogrammetry.

Austin E. Jones of Rogue River, Oregon, has accepted an assignment by the U. S. Geological Survey to operate seismographs and collect earthquake and volcanologic data in the vicinity of Adak, Alaska.

Louis D. Kaplan has undertaken studies on the problem of atmospheric heat transfer by infrared radiation at the University of Chicago on behalf of the U. S. Weather Bureau.

Raymond B. Montgomery, Physical Oceanographer with the Woods Hole Oceanographic Institution has been appointed Professor of Oceanography at Brown University.

Howard J. Pincus has accepted a position as Instructor in Geology at Ohio State University.

Paul A. Rechard, who received his Master of Science degree from the University of Wyoming in June 1949, has been appointed Hydrologist in the office of Region Six of the Bureau of Reclamation, with headquarters in Billings, Montana.

William F. Uhl, President of Chas. T. Main, Inc., Consulting Engineers, has been awarded an honorary degree of Doctor of Engineering by Tufts College.

Ralph H. Wilpolt has resigned his position with the U. S. Geological Survey and accepted the position of Chief Geologist with the Clinchfield Coal Corporation with headquarters at Dante, Virginia.

Cecil S. Camp, Director of the School of Hydraulic Engineering at Louisiana State University, his wife, and two children were killed in a tragic automobile accident on October 16, 1949. He was born at Marche, Arkansas September 17, 1907, received his baccalaureate degree from the University of Arkansas in 1929, and his Master of Science degree from the University of Iowa in 1937. Prior to the receipt of the degree of Master of Science, he engaged in diverse engineering work, including teaching at Oregon State College. Following his studies at the University of Iowa, he returned to teaching at Syracuse University, at the University of Tennessee, and subsequently took up duties at Louisiana State University. He had been a member of the AGU since 1940.

Stephen Reid Capps, Geologist with the U. S. Geological Survey in Washington, D. C., died January 19, 1949 at the age of 67. He was born in Jacksonville, Illinois, entered Illinois College in 1899, received his baccalaureate degree from the University of Chicago in 1903, and the degree of Doctor of Philosophy from the same school in 1907. He entered the service of the U. S. Geological Survey in 1907 and continued until his death, though in the early 1920's he undertook consulting work in the Near East for the Standard Oil Co. of New Jersey. He was the author of many papers bearing on geology and mineral resources in Alaska, Brazil, the Near East, and other areas.

Nephi Willard Cummings of San Bernardino, California died October 31, 1949, at the age of 60. He was born in Salt Lake City, received his baccalaureate degree from the University of Utah in 1913, and his degree of Doctor of Philosophy from California Institute of Technology in 1926. The early part of his professional career was spent at Scripps Institution of Oceanography and San Diego State College. Following the receipt of the doctorate, he devoted a year to research work with the Standard Oil Co. of California. In 1927, he took up duties as head of the Physics Department and Chairman of the Division of Sciences of San Bernardino Valley Union Junior College which he continued until his retirement in 1945. His chief work was in the fields of meteorology and physical oceanography with emphasis on energy-evaporation relationships on which he published several papers in the Transactions. He had been a member of AGU since 1931.

William Jackson Humphreys, meteorological physicist retired from the United States Weather Bureau, and Professor Emeritus of George Washington University, died November 10, 1949, at the age of 87. He was born at Gap Mills, West Virginia, in 1862. He received his baccalaureate degree from Washington and Lee in 1886 and a professional degree in Civil Engineering in 1888. In 1888 and 1889, he took advanced work in chemistry and physics at the University of Virginia, and received the Doctor of Philosophy degree from Johns Hopkins in 1897. His diverse and versatile professional career began as Professor of Physics and Mathematics at Miller School, Virginia, and after other teaching assignments, he became Director of the Mt. Weather Observatory, Virginia, in 1905. He continued his association with the Weather Bureau in various capacities until 1936. From 1911 to 1933, he was Professor of Meteorological Physics at George Washington University. He took part in various expeditions, and was the recipient of numerous medals, awards, and other honors.

His outstanding scientific career is well known to workers in the Earth Sciences everywhere. His most outstanding contribution was "Physics of the Air" in which the principles of meteorology were treated in a logical, thorough, and elegant manner. The world-wide demand for a book of this kind was so insistent that it went through three revisions in order to embody in it the numerous later developments. Its clarity of diction and the manner of presentation were models of excellence, and it served as an outstanding text book in the science in many countries for a number of years.

His ability to translate scientific findings into form understandable and readable to the general public has endeared him to many an American household. Though his chief work was in the meteorological sciences, his broad interests carried him into seismology, optics, diffusion of metals, analyses of spectra, and other fields of science.

He had been a member of AGU since 1920, and served as its second General Secretary from 1921 to 1922. He was President of the Union from 1932 to 1935; of the Section of Seismology from 1922 to 1924; and Vice-President of the Section of Meteorology from 1920 to 1922.

Frederick H. Paget, Hydraulic Engineer with the California Division of Water Resources and chief of the cooperative snow survey work in that State died on September 16, 1949. He was born in Nova Scotia in 1898. He attended Magill University, and later the University of California from which he received his baccalaureate degree. In 1920 he entered his professional career in irrigation and drainage. He entered the services of the Division of Water Resources in 1930, and continued in that work until his death, except for a three-year tour of duty with the U. S. Forest Service from 1933 to 1936. He had been a member of AGU since 1942.

Alfred Senn, stratigraphic geologist of Binningen, Switzerland, died in January 1949, at the age of 50. He was born in Basle, Switzerland, studied at the Universities of Neuchatel, Paris, and Basle, and received the degree of Doctor of Philosophy from the University of Basle in 1924. His professional work in stratigraphy related largely to oil, and took him for various periods to Venezuela, North Africa, and the British West Indies.

Earnest Stanley Shepherd, retired Research Chemist of the Geophysical Laboratory, Carnegie Institution of Washington died September 29, 1949, at the age of 70. He received his baccalaureate degree from Cornell in 1902 and entered his professional career as a private assistant to Wilder D. Bancroft. In 1904 he entered the service of the Geophysical Laboratory, Carnegie Institution of Washington, where he continued until his retirement in 1945. His chief work was in the fields of geochemistry and volcanology. He had been a member of AGU since 1929.

Raymond Latimer Stevens, Hydraulic Engineer on the staff of the Secretary, U. S. Department of Agriculture, died August 11, 1949. He was born in 1905 at Hyattsville, Maryland, and received his baccalaureate degree in civil engineering from the University of Maryland in 1927. His early professional career was with the Maryland State Roads Commission, with the County Engineer of Montgomery County, Maryland, and as a construction engineer on the Memorial Bridge over the Potomac between the District of Columbia and Virginia. In 1935, he entered the service of the Soil Conservation Service in the Department of Agriculture and continued in various capacities in the Department on hydraulic and flood control problems until his death.

Transactions, American Geophysical Union Volume 30, Number 6 December 1949

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION,

Meeting of October 28, 1949

The meeting was called to order in the Board Room of the National Research Council - National Academy of Sciences Building, 2101 Constitution Avenue, Washington, D. C. at $13^{h}40^{m}$ by President Walter H. Bucher.

Present--Twenty-nine persons were present, namely: L. H. Adams, K. Hilding Beij, Merrill Bernard, Walter H. Bucher, Wilbur S. Burbank, Ernst Cloos, Frank L. Culley, Jno. A. Fleming, Richard H. Fleming, H. D. Harradon, Henry W. Hemple, Benjamin Holzman, Earl Ingerson, Woodrow C. Jacobs, H. Freeborn Johnston, J. W. Joyce, David G. Knapp, W. D. Lambert, Ray K. Linsley, Jr., J. Putnam Marble, A. G. McNish, G. Medina, Frank Neumann, F. W. Reichelderfer, Florence Robertson, Irwin Roman, James B. Small, Waldo E. Smith, and Walter D. Sutcliffe.

The following were excused because of absence from the city or for other reasons: Fred Anderegg, Robert Balk, Arthur Bevan, J. Bjerknes, Detlev W. Bronk, Perry Byerly, H. R. Byers, J. E. Church, Ralph E. Cleland, Richard E. Fuller, M. King Hubbert, C. O'D. Iselin, C. E. Jacob, J. B. Macelwane, George F. McEwen, Martin A. Mason, Ed. H. Smith, V. C. Stechschulte, H. T. Stetson, Lorenz G. Straub, W. T. Thom, Jr., F. J. Veihmeyer, Francis G. Wells, George P. Woollard, and Raymund L. Zwemer.

Approval of Minutes--The Minutes of the Executive Committee meeting of April 23, 1949, as published in the August 1949 issue of the Transactions, pages 616 to 621, were approved.

General Secretary's Report

Office Personnel--We have had considerable changes since our last meeting. Mrs. Edward A. Krizay, Electromatic Operator and Editorial Assistant, resigned as of June 1, 1949, and her work is now in the hands of Mrs. Geraldine L. Lamb. Mrs. Eleanor T. Ager resigned as of August 9, 1949; her position has been filled by Mrs. Ida A. Edwards. Mrs. Sherman F. Fortner, Jr. succeeds Mrs. James L. Parkes.

Financial Report--A detailed financial statement was prepared as of June 30, 1949, and referred to the Committee on Audit. (See Appendix 1 for Committee's report and statement.) The cash balance on December 31st is expected to be very low, probably the lowest in the recent years of the Union's existence, reflecting the urgent need for the increase in dues which will become effective January 1, 1950.

Membership--The Membership Committee is now fully organized and despite the summer season has done very well. The net increase in membership since April 20, 1949, is 124. Last April it was reported that 102 members were delinquent two or more years; of these 87 have been dropped. It was also reported that 27 new members had not responded to notices of their election and of these 20 have been dropped. Thus there is no dead wood in the total as it stands today although quite a number are in arrears in dues for 1949 (333) and for 1948 and 1949 (122). Past experience has shown that many of these will pay their dues and become members in good standing. The following is a summary since April 20, 1949.

Members, April 20, 1949	4,449	
New members	291	
Reactivated	5	4,745
Resignations	44	
Deceased	13	
Inactive	4	
Dropped for non-payment of dues	87	
Dropped, new members	20	168
Membership, October 26, 1949		4,577

Thirteen deaths have been reported since April 20, 1949; namely, Edwin L. Moseley, June 6, 1948; G. K. Greening, July 31, 1948; Alfred Senn, January 1949; Arthur M. Morgan, February 5, 1949; Harry Leypoldt, February 6, 1949; Edward B. Stephenson, May 6, 1949; Philip S. Smith, May 10, 1949; Lawrence F. Hanks, June 30, 1949; Raymond L. Stevens, August 11, 1949; Wm. J. Rooney, August 31, 1949; Fred H. Paget, September 16, 1949; Earnest S. Shepherd, September 29, 1949; and Cecil S. Camp, October 16, 1949.

Two names have been added to our list of Life Members through retirement; namely, H. D. Harradon who has been a member since 1930, and F. R. Moulton who has been a member since 1921.

Corporation Membership--As in April, we have now four Corporation Members whose cards are published in each issue of the Transactions.

Administration of the Union--The Unions's offices remain in the Administration Building of the Carnegie Institution of Washington although moved to another portion of the building. At the close of the year or early next year the officers of the Union will again request a continuance of the present arrangement with the Carnegie Institution.

In May a tabulation of the Section affiliations was made. A copy of the resulting information was mailed out to all Executive Committee members and Section officers. At the time there were 4,501 members of whom 985 had affiliation with Geodesy; 1256, Seismology; 1,660, Meteorology; 938, Terrestrial Magnetism and Electricity; 872, Oceanography; 784, Volcanology; 2,140, Hydrology; and 1,101, Tectonophysics; a total of 9,736 affiliations. Thus, 10 per cent are in Geodesy, 13 per cent in Seismology, 17 per cent in Meteorology; 9 per cent in Terrestrial Magnetism and Electricity, 9 per cent in Oceanography, 8 per cent in Volcanology, 22 per cent in Hydrology, and 11 per cent in Tectonophysics.

President Bucher appointed a Special Advisory Committee consisting of F. W. Reichelderfer, Chairman; L. H. Adams; H. N. Eaton; E. A. Eckhardt; and H. W. Hemple to study the Tuve proposal relating to the Journal of Geophysical Research discussed at the Executive Committee meeting in April.

National Research Council -- The term of Ernst Cloos as AGU representative in the Division of Geology and Geography expired June 30 and W. T. Thom, Jr., has been designated in his place.

The Chairman of the Division of Mathematical and Physical Sciences requested the counsel of the officers of AGU in the naming of three new members to the Special Advisory Committee on Geophysics to the ONR to succeed David Griggs, W. C. Krumbein, and Maurice Ewing. Two recommendations were made for each vacancy.

Meetings--The resolutions passed at the Thirtieth Annual Meeting held in Washington last spring have been duly forwarded to the organizations concerned and quite a large number of favorable responses have been received.

The Twenty-Fifth Regional Meeting is to be held in Davis, California, February 3 and 4, 1950, with the Sections of Hydrology and Meteorology taking part. F. J. Veihmeyer has been designated as Chairman of the Union Committee arranging this meeting with J. C. Marr of Davis, California, as the representative of the Section of Hydrology, and the representative of the Section of Meteorology yet to be designated. (E. M. Vernon has since been designated for the Section of Meteorology--Ed.)

Plans for the Thirty-First Annual Meeting are progressing well and alternative schedules have been tentatively set up for a meeting of two sessions simultaneously extending over four days, or of three sessions simultaneously extending over three days.

Publications --We are continuing to publish our bimonthly Transactions in an edition of 5,200.

Work is progressing on the index for the first 25 years of the Transactions and it is hoped that this index will be ready for the printer about the first of January.

United Nations--The United Nations Scientific Conference on the Conservation and Utilization of Resources convened at Lake Success August 17 to September 6, 1949. Ralph M. Leggette was designated as AGU representative at this gathering. His report will appear in the December issue of the Transactions.

American Standards Association-- Arrangements have been completed for the establishment for the Committee on Fluid Permeation, Z59, under the joint sponsorship of the Geological Society of America and the American Geophysical Union. This Committee is now being organized under the Chairmanship of C. E. Jacob who was instrumental in bringing it into being. C. E. Jacob, together with Frank L. Duley, Sterling J. Richards, L. A. Richards and W. O. Smith, have been named AGU representatives on the Committee.

Seventy-Fifth Anniversary of the Founding of the Colorado School of Mines--The American Geophysical Union received an invitation to send a representative to the Seventy-Fifth Anniversary of the Founding of the Colorado School of Mines. President Bucher designated Roy W. Goranson.

Miscellaneous--A statement covering the activities of the AGU has been prepared for inclusion in the next issue of the Geophysical Directory, Houston, Texas.

The International Union of Geodesy and Geophysics requested copies of old programs of AGU annual meetings to serve as guides in preparing a printed program for the Assembly, 1951, in Brussels.

The American Meteorological Society has now undertaken the publication of meteorological abstracts and bibliographies, this being sponsored and supported financially by the Air Weather Service of the Air Forces. The question might well be raised whether it would not be a good idea for a bibliography to be prepared in the broad field of geophysics. Should proper sponsorship be found it is believed that such an undertaking would be very much worth while.

The attention of the Committee is called to the series of seminars that are being held under the auspices of the Geophysical Research Directorate of the Air Force Cambridge Research Laboratories as planned by the Chief of Plans and Operations Section of the Base Directorate for Geophysical Research.

A Joint Meeting of the USA National Committee, International Scientific Radio Union, and Professional Group on Antennas and Wave Propagation of the Institute of Radio Engineers is to be held in Washington October 31 to November 2.

A communication has been received from the Standard Oil Company's Educational Service, soliciting the aid of AGU in preparing a list of names of those who might well be recipients of publications bearing on various aspects of research and oil being prepared by the Standard Oil Company.

The attention of the Committee is invited to the fact that one of the editors, Walter B. Langbein, has now for about two years accepted only $5.00 of the full amount of his honorarium of $75.00 for each half year. This gracious act has been acknowledged with thanks by the President and the funds thus made available have been transferred to the Permanent Fund of the Union.

The American Petroleum Insititute is to meet in Chicago November 7 to 10, inclusive, for its Twenty-Ninth Annual Meeting.

Action on the General Secretary's report--The report was accepted.

International Relations

Honorary President Fleming reported on developments concerning the International Union of Geodesy and Geophysics and the International Council of Scientific Unions as they relate to the policy of the State Department. He outlined what appears to be a change in policy of the State Department pertaining to support through its budget for international organizations. That policy may eliminate support to the International Council of Scientific Unions and its Unions from the Department after June 30, 1951. He indicated that any such action might concern some 45 "non-governmental" international organizations. He pointed out the great influence and value of the International Council of Scientific Unions and its constituent Unions, and it would indeed be a calamity if this work were not continued. The National Research Council's Committee on the International Council of Scientific Unions is studying this problem and feels that possibly some contractual arrangement between the National Research Council, the National Academy of Sciences, and the State Department can be worked out. There would be great difficulty in having individual organizations without any governmental status undertake this relationship inasmuch as in most countries the Unions of the ICSU have governmental support from their Departments of Foreign Affairs.

There was extensive discussion, and a motion was made and approved that the President be empowered to appoint a committee on this matter should the situation warrant.

Reports of Standing Committees

Membership--Chairman Small indicated that the present rate of additions of new members is about 50 per month and he believes that this will be maintained.

Subcommittee on Corporation Membership--Chairman Roman reported that work is progressing. Since the effort began we have secured four corporation members and more are believed to be in early prospect.

Meetings--Chairman Marble made an announcement concerning the Twenty-Fifth Regional Meeting to be held in Davis, California, February 3 and 4, 1950, with the Sections of Meteorology and Hydrology participating.

With regard to the Thirty-First Annual Meeting to be held in the opening days of May 1950 he raised the question whether a three-day schedule spread out in space or a compactly four-day schedule, all under one roof, is preferable. There was considerable discussion following which the Executive Committee went on record as leaving the matter to the best judgment of the Committee on Meetings, expressing preference for a three-day schedule that is quite compact geographically. It was thought that the public auditorium in the old Interior Building rather than the Interdepartmental Auditorium might offer a third meeting room that is less remote in distance.

Nominations--In the absence of Chairman Macelwane the report of the Committee was read indicating the nominees for President to be Walter H. Bucher, Ernst Cloos, and Maurice Ewing; for Vice-President to be Perry Byerly, F. W. Reichelderfer, and L. B. Slichter; for General Secretary to be K. Hilding Beij, J. Putnam Marble, and J. Frank Shairer. Attention was called to the fact that the Executive Committee was to act on this report in accordance with item (3) of the procedure set up in 1946, namely, "that such nominations then be submitted by the Nominating Committee to the Executive Committee, which body may accept the report or add other nominees for such offices. It will then proceed to select by secret ballot not less than two official nominees for each office." On the suggestion of the President the nominees present withdrew and the President turned the chair over to Honorary President Fleming. After extensive discussion the report was approved as it stood. In the discussion it was brought out that the Statutes (Article 5) provide "that the President and Vice-President shall not be eligible for immediate reelection--." The incumbents were both designated by the Executive Committee to complete unexpired terms, and have thus not been elected. As they stepped into the breach at critical times, the Executive Committee concurred with the Committee on Nominations that such emergency service should not preclude their nomination to the offices they are now filling. The nominees were invited to return. It was pointed out that three nominees are indicated and it was confirmed that point (8) of the procedures, namely, "that a plurality of votes cast shall elect" be followed.

Audit--Chairman McNish reported that the accounts of AGU for the fiscal year ending June 30, 1949, had been audited and found in order. The auditors' report is presented as Appendix 1.

Reports of Special Committees

Committee on Journal of Geophysical Research--Chairman Reichelderfer presented an interim report on the Committee's work (see Appendix 2) following which there was extensive discussion of the report and the proposal in general. The main issues revolved about two points; first, the wisdom of segregation of certain papers for publication in a letter-press journal; and second, the financial aspect. With regard to the first there was discussion pro and con but with regard to the second there seemed to be no acceptable answer as yet to the question of the increased cost, when with increased dues the Union will only now find itself in a position to balance its budget. Further study is to be undertaken with consideration given to the feasibility of different membership charges for the possible combinations of membership and Journal subscription, with a similar plan of subscription not involving membership. The report was approved with instructions to the Committee to continue its deliberation and to bring in a report at the next meeting of the Executive Committee.

Committee on Regionalization--Chairman Bernard presented the report setting forth definite recommendations for establishing a very flexible regional plan. This report was adopted by the following motion, "that the President be empowered to implement the recommendations of the Regionalization Committee by January 1, 1950, unless any serious objections are submitted in writing before that time by any member of the Executive Committee." The report with other pertinent information appears as Appendix 3.

American Geological Institute--Representative Cloos on the Board of the American Geological Institute advised that the Institute is now a going organization and is becoming active in various fields, and that its Committees will meet at the El Paso convention of the GSA in November. He mentioned also that the term of one of the members of the Board expires November 30, 1949 (the President has reappointed Dr. Cloos to a full two-year term). Representative Thom who was unable to attend the Executive Committee meeting called attention by letter to Volume 1, Number 1 of AGI News issued September first and that in substance constituted his report to AGU on AGI activities.

New Business

A letter was read from a national scientific society in which the hope was expressed that one of the officers of the AGU who is a Fellow of that society might in his official capacity offer his endorsement of this national society to our members, encouraging them to become members of that society. After discussion it was voted that, an officer of the AGU, in his capacity as such an officer, may not act as sponsor for membership in any other organization.

The question was raised concerning affiliation with the AAAS. A statement was read from the Executive Secretary of AAAS outlining in general terms what the status of affiliation might imply. While it was felt that affiliation might be mutually beneficial, the Executive Committee desired specific information before action and directed the Executive Secretary to investigate all the implications, practical and idealogical, that would be involved in affiliation with the AAAS, and what could be gained and what could be given at present and in the future in such a relationship.

Johnston raised the question concerning procedures in the Editorial and Publication Committee, and after discussion a motion was passed that the Committee should report on the methods used in accepting papers for publication in the Transactions at the next meeting of the Executive Committee.

Adjournment--The meeting adjourned at $17^{h}00^{m}$.

K. HILDING BEIJ, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX 1--REPORT OF COMMITTEE ON AUDIT FOR FISCAL YEAR

JULY 1, 1948 to JUNE 30, 1949

A. G. McNish (Chairman), R. H. Weightman

Your Committee on Audit has examined the books of the Union for the fiscal year ending June 30, 1949, and found them in agreement with the statement of the Union's finances supplied by the Executive Secretary which is attached hereto.

The cash assets and investments of the Union at the beginning of the fiscal year amounted to $19,374.60 of which $13,341.89 was held as cash reserve, $2,368.00 in the permanent fund, $3,531.41 in the Horton Fund, and $133.30 in the Bowie Medal Fund.

Receipts for the year from all sources totaled $27,659.37 while expenditures totaled $34,233.95. This deficit included $2,172.00 used for preparation of the Horton papers and $13.00 used for the Bowie Medal, which amounts were drawn from the respective funds set up for those purposes. The balance of the deficit, $4,389.58, was drawn from the cash reserve of the Union. A transfer of $400.00 from the cash reserve to the permanent fund was made during the year.

At the end of the year the cash assets and investments of the Union was $12,800.02 of which $8,552.31 was held as cash reserve, a decrease of $4,789.58; $2,768.00 was held in the permanent fund, an increase of $400.00; $1,359.41 was held in the Horton Fund, a decrease of $2,172.00; and $120.30 was held in the Bowie Medal Fund, a decrease of $13.00.

Your Committee on Audit finds that the new form in which the financial statement was submitted for the year is more descriptive of the fiscal affairs of the Union than those submitted in previous years but is less satisfactory for auditing purposes.

Statement of assets and liabilities as of June 30, 1948

Assets			
Cash Reserve	$13,341.89		
Robert E. Horton Fund	3,531.41		
William Bowie Medal Fund	133.30	$17,006.60	
Permanent Fund (in series F bonds and building and loan association)		2,368.00	$19,374.60
Bills receivable			5,305.81
	Total assets		$24,680.41

Liabilities	
Bills payable	$ 268.21
Surplus (capital account)	24,412.20
	$24,680.41

Operating Statement

(Fiscal year ending June 30, 1949)

Receipts			
Grants			
National Research Council			$ 400.00
Income			
Dues 1946-1950 et seq			
1946	$ 20.00		
1947	150.00		
1948	2,384.83		
1949	17,912.06		
1950 et seq	127.00		
Life Memberships (two 1948 and one 1949)	300.00		
Corporation Memberships (three 1948 and one 1949)	400.00	$21,293.89	
Sales, Transactions		3,302.98	
Sales, Reprints		1,346.57	25,943.44
Payment for Third and Fourth Quarters under RDB Contract			1,250.00
Miscellaneous contributions			65.93
			$27,659.37
Disbursements			
Publishing Transactions			
Printing		$ 7,[illegible].23	
Preparing manuscript		2,762.36	
Time of Executive Secretary		~~3,000.00~~ 2860.00	
Envelopes and preparation for mailing		456.72	
Postage		400.32	$14,010.63 ✓
Reprints			1,060.75
General Expenses, Office of Union			
Salaries for services		$11,301.70	
Stationery and supplies		885.47	
Postage and communications		1,081.57	
Office equipment		725.40	13,994.14 ✓
Expenses, meetings			
Annual Meeting		$ ~~331.55~~	
Regional Meetings		~~95.86~~	~~427.40~~ ✓
Expenses, Sections			35.15
Expenses, Committees			190.44
List of Members and Officers			984.57
Honoraria to co-editors			1,210.00
Travel of Officers			135.87
Robert E. Horton papers			~~2,172.00~~
William Bowie Medal			13.00
			$34,233.95 ✓
Investment (Transferred to Permanent Fund)			400.00
			34633.95

Excess of expenditures over receipts

Expenditures		$34,233.95
Receipts		27,659.37
Excess		6,574.58
Drawn from Robert E. Horton Fund	$ 2,172.00	
Drawn from William Bowie Medal Fund	13.00	
Drawn from Cash Reserve	4,389.58	$ 6,574.58

Statement of assets and liabilities as of June 30, 1949

Assets			
Cash Reserve	$ 8,552.31		
Robert E. Horton Fund	1,359.41		
William Bowie Medal Fund	120.30	$10,032.02[a]	
Permanent Fund		2,768.00	$12,800.02
Bills receivable			4,935.86
			$17,735.88
Liabilities			
Bills payable			337.64
Surplus (capital account)			17,398.24
			$17,735.88

12800.02✓
2768
15568.02

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[a] Riggs National Bank per statement of June 30, 1949 — $13,478.01

Less checks outstanding:

No. 3017	$1281.08	No. 3031	$ 75.00
3018	7.73	3032	75.00
3019	32.17	3033	5.00
3020	14.26	3034	75.00
3021	2.06	3035	75.00
3022	1.50	3036	264.16
3023	22.87	3037	114.50
3024	6.00	3038	78.07
3025	627.98	3039	75.03
3026	40.80	3040	70.93
3027	75.00	3041	39.55
3028	75.00	3042	2.40
3029	75.00	3043	8.10
3030	75.00	3044	151.80

Total checks outstanding	$ 3,445.99
Balance June 30, 1949, as above	$10,032.02

Investments, June 30, 1949 (Permanent Fund)		
Prior to July 1, 1948, Series F Bonds, maturity value $3,200, at cost	$2,368.00	
During fiscal year, deposited in Northwestern Federal Savings and Loan Association	400.00	$ 2,768.00
Bills receivable, June 30, 1949		
Publications		$ 525.86
Transactions	$ 234.93	
Reprints	290.93	
Dues		4,410.00
1949, 608 members	$3,040.00	
1948 and 1949, 137 members	1,370.00	
Total bills receivable		$ 4,935.86
Bills payable and advance payments, June 30, 1949		
Doubleday-Hill Electric Co. (equipment)	$ 107.84	
A. B. Dick Co. (stationery and supplies)	8.80	
Dues and subscriptions paid in advance (1950)	221.00	
Total bills payable		$ 337.64

Equipment owned by American Geophysical Union

One Globe-Wernicke, 2-pedestal, flat-top steel desk, AGU No. 1, 60 × 34 inches	$ 49.18
One walnut flat-top desk, AGU No. 2, 34 × 66 inches, with glass top	95.43
One walnut typewriter desk, AGU No. 3, 34 × 66 inches, with glass top	100.72
One Globe-Wernicke No. 526 TW imitation-walnut desk, 55 inches, Dept. No. 99	31.51
One General Fireproofing steel typewriter desk, green right pedestal type, 34 × 60	113.75
Two steel posture chairs	22.00
One walnut chair	21.50
One No. 617 posture chair with olive green finish, genuine brown leather upholstery, Dept. No. 254	7.00
One wood revolving chair, Dept. No. 148	0.00
Two wood typewriter chairs, revolving, Dept. Nos. 31 and 131	0.00
One 18-inch larger primer Burroughs typewriter, serial No. 60A232450	190.80
One 10-inch elite Royal typewriter, serial No. KHM-2076351	100.31
One 11-inch elite Underwood typewriter, serial No. 11-6126347	129.43
One 11-inch elite Underwood typewriter, serial No. 11-6194757	129.43
One Elliott Addressing Machine, model 80, serial No. 102285 B, on stand	315.99
Twenty-seven tray cabinet (Elliott) with short tray, 27 short trays with fronts and 27 short trays with connecting clips	75.71
Four steel file cabinets from Globe-Wernicke No. 7341, letter size, No. 24, green	193.60
Two 4-inch drawer, 3 × 5 inch steel filing cases (gift)	0.00
One Triner postal scale 4 lbs. by 1/2 oz.	16.20
One Arrow stapler	6.75
One costumer, walnut finish	3.50
One costumer, walnut finish	7.60
One 15-inch Eastman trimmer	13.50
One Hallowell 28-inch steel stool, No. 70	1.00
One three-fold double burlap screen brown, oak finish	2.00
One three-section open bookcase composed of book sections Nos. 36, 100, and one old section without number, and book section top No. 108	1.00
Ten desk trays, walnut finish	14.00
Twelve copies, Manual of Style, University of Chicago Press	32.50
One Klera-desk	3.70
Two Emeralite gooseneck lamps, Nos. 110 and 117 at $1.00 each	2.00
One white table	1.00
Two pieces Masonite, each 3 ft × 4 ft	0.00
One book rack	1.00
One work table on trestles	3.90
One Session office clock	5.44
Two Dazor lamps with stands	48.30
Two Dazor lamps with clamps	32.10
One IBM electromatic typewriter, 12-inch carriage, bold face type	627.98
Two file cabinets, green metal Artsteel, 2-drawer units	10.08
Mimeograph duplicator, A. B. Dick Company machine (gift)	0.00
Total cost of equipment	$2409.91

[Note: The Union has a large stock of Transactions of past years available for sale, but these are carried as without value in the inventory.]

APPENDIX 2--PRELIMINARY REPORT OF THE SPECIAL COMMITTEE ON THE PROPOSAL FOR A NEW JOURNAL OF GEOPHYSICAL RESEARCH

F. W. Reichelderfer, Chairman

L. H. Adams E. A. Eckhardt
H. N. Eaton H. W. Hemple

In his letter dated June 13, 1949 to the Chairman of the Special Committee, President Bucher instructed the Committee to "confer with the Editorial and Publications Committee concerning Dr. Tuve's proposal, to gather necessary information from the outside and report to the Executive Committee at the October meeting if possible." In his letter of June 11 to Members of the Executive Committee, President Bucher also requested its members to "give this important matter the most careful thought and discuss it, as far as possible with members of the Executive Committee of your section, if you are President of a section" and to send findings and ideas to the Special Committee.

Accordingly, the comments of eleven members of the Executive Committee who have so far expressed their views together with the comments of its own members were reviewed and discussed in a meeting of the Special Committee on October 20th. Committee members also have made preliminary inquiries among those with experience in the publication of scientific journals and in particular those with experience in the financing of publications in other scientific organizations; for example the American Physical Society and the American Meteorological Society.

As is to be expected in a subject as important and subjective as this there is wide divergence of opinion, both as to the need for and desirability of inaugurating a new journal of geophysical research and as to the financial practicability thereof.

On the basic question as to need for and desirability of a new outlet for papers in theoretical geophysics, there appears to be almost unanimous appreciation of the opportunity that lies before the American Geophysical Union to take the leadership in providing a new periodical for exchange of knowledge in geophysics and foster progress in research in the interrelated sciences in this field. One or two have recommended strongly that the Union go further and contribute more broadly to the welfare of geophysical sciences by immediately bringing other geological and geophysical organizations into consideration of the plan.

Although several different objections or disadvantages have been pointed out, some of them mentioned in the enclosures to President Bucher's letter of June 11, it seems to be the majority opinion that a strong case can be made in favor of a new journal from the viewpoint of desirability.

We are informed that there is sufficient volume of good papers to justify a separate journal in theoretical geophysics and promise of a continued flow of suitable research papers in the future. The objections and unfavorable implications are not discussed in this report in view of the fact that further investigation is necessary before sound conclusions can be reached.

Practically all agree that the crux of the matter is the financing. No practical solution has been found to the problem of financing a new periodical up to the present time. Individual opinions on the financial aspects vary all the way from those who think the problem can be solved if attacked with courage and vision to those who feel that economic uncertainties and the difficulties experienced by other scientific journals make it very doubtful that a new journal in geophysics can be successfully financed during the next few years.

The subject is too large in its scientific and organizational implications as well as in its financial aspects for the Special Committee to offer definite conclusions and recommendations at this time. It has been discussed with the Chairman of the Editorial and Publications Committee and it is the opinion of that Committee that further study and consideration are necessary. There are several questions on which the members of the AGU will wish to be informed before they are ready to vote on the proposal and some of these questions will require further information from other interested scientific organizations and from the representatives of other journals that may be affected by the plan.

If the Special Committee is to continue its work and attempt to arrive at definite recommendations, the Committee would like further expression of views by members of the Executive Committee and will welcome suggestions or guidance from the President or the Committee on how far the study should go before the membership of the AGU as a whole is invited to express its views.

APPENDIX 3--REPORT OF THE SPECIAL COMMITTEE ON REGIONALIZATION

Merrill Bernard, Chairman

H. H. Hess
Earl Ingerson
J. P. Marble
G. Medina

At its meeting of December 3, 1948, the Executive Committee of the Union authorized its President to appoint a special committee to "... study the problem of regionalization to determine whether or not regionalization is desirable for the Union and, if so, to develop a tentative plan for consideration by the Executive Committee."

The Committee held its first meeting on February 10, 1949. In approaching the problem, the Committee found itself the beneficiary of two previously prepared analyses on regionalization -- one by J. P. Marble, Chairman, Committee on Meetings; the other made under the auspices of the Section of Hydrology. Discussion, however, quickly pointed to the necessity for a much broader basis of opinion and, accordingly, a survey was agreed to which would, in a systematic way, sample and express in composite the opinion of the Union membership residing outside Washington, D. C.

Twenty cities were selected which, in addition to representing geographical distribution, were recognized centers of geophysical interest. A memorandum was addressed to from six to eight Union members in each city, with special effort made to have all Sections having local members represented.

The Committee's request for advice was taken seriously, and while the survey returns do not lend themselves to a tally count, the committee believes conclusions drawn from them can be accepted as the basis for action by the Executive Committee. These conclusions are:

(1) There does not exist a large positive opposition to the idea of regionalization, only seven or eight regional group members having expressed definite opposition.

(2) The majority of responses ranged from non-committal to enthusiastic. Those voicing milder interest made note of the fact that their particular field (and, therefore, the Union section of greatest interest to them) was adequately represented by an established national society whose functions included provision for regional and joint meetings. The less analytical replies dismissed the matter by saying that "there are already too many scientific societies calling for meetings over the country."

(3) The greatest support for regionalization came from those with major interest in the Section of Hydrology. The Committee quickly reached the conclusion that this is accounted for in the fact that hydrology, as one of the more recently established natural sciences, does not have a national society and is, in fact, utilizing the Section of Hydrology of the Union to express its national policies and program. It was for this reason that the Section of Hydrology first felt the need for a regional organization and expressed that need in a memorandum to the Executive Committee at its meeting on November 28, 1947 [Trans., v. 29, p. 47, Feb. 1947].

Early in its deliberations, the Committee on Regionalization reached unanimous agreement on certain basic considerations which can now be stated as conclusions. These are:

(1) That the Union, being an organization dedicated to the advancement of the natural sciences, shall not be burdened with costly time and energy-consuming administrative and supervisory machinery.

(2) The primary purpose of regionalization would be to provide the means for promoting, organizing, and conducting section meetings or joint section meetings at strategically selected points throughout the country in addition to the Annual Meeting of the Union held in Washington, D. C.

(3) That the regional organization should be only moderately formalized, allowed considerable autonomy, and be discouraged from building up regional "machines," found frequently in some organizations.

(4) Although for organizational purposes definite regional boundaries are advisable, the regional organizations would be encouraged to invite members from other regions to participate in their meetings.

(5) That while there is at present a considerable range in attitude toward regionalization, ultimately all sections may find it desirable to collaborate.

The Special Committee on Regionalization is prepared to report affirmatively on the question, "whether or not regionalization is desirable for the Union." It, therefore, presents recommendations outlining a tentative plan should the Executive Committee elect to regionalize the Union's activities.

Recommendation (1): The United States will be divided into eight regions as outlined tentatively in Figure 1. The principal factor in delineating regions is mutuality of interest and geographic distribution of membership. The regions shall be named rather than numbered for reference purposes, for example, "Northeastern Region," and "South Pacific Region," members outside of the United States would participate in the activities of regions most convenient to them, according to their desires.

Recommendation (2): The Regional Committee shall be comprised of not more than three members from each of the Sections electing to participate in the activity of a given region. This would result in a working committee of six where a meeting involving two sections is planned, and at the same time allow each section to have a three-man committee if operating alone, for a time, in any region. Subcommittees and working groups will, of course, be authorized by Regional Committees whenever such are found to be necessary.

Recommendation (3): This recommendation is in the form of a suggestion to implement regional

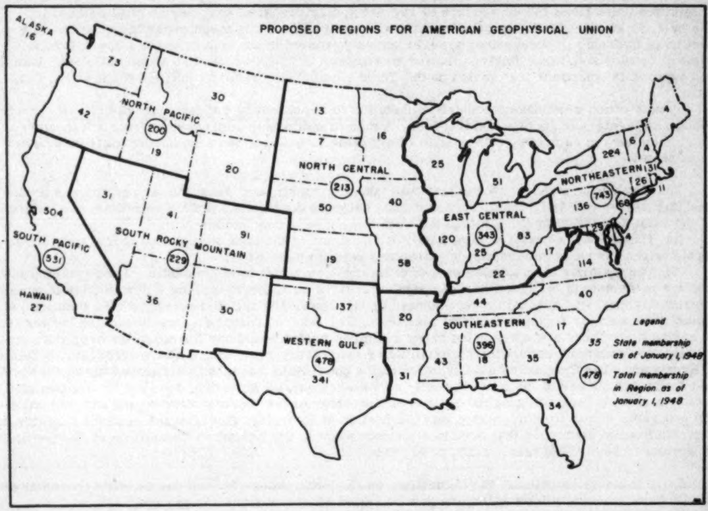
PROPOSED REGIONS FOR AMERICAN GEOPHYSICAL UNION
ALASKA
16
73
42
NORTH PACIFIC
200
30
19
20
13
7
16
NORTH CENTRAL
213
50
40
25
51
EAST CENTRAL
343
120
25
83
22
17
114
40
4
224
6
4
NORTHEASTERN
743
31
26
11
136
68
29
4
31
504
SOUTH PACIFIC
531
41
SOUTH ROCKY MOUNTAIN
229
91
19
58
HAWAII
27
36
30
137
20
44
SOUTHEASTERN
396
18
43
35
17
WESTERN GULF
478
341
31
34
Legend
35 State membership as of January 1, 1948
478 Total membership in Region as of January 1, 1948

Fig. 1--Proposed regions for American Geophysical Union

activity (Attachment A). (Sample By-Laws should also be prepared if the plan is to be implemented.)

Recommendation (4): The Section of Hydrology has, for reasons discussed in this report, perhaps the most immediate interest in regionalization. It is recommended, therefore, that the Section of Hydrology be requested to implement the program of regionalization, with the express admonition that it at all times encourage and make provision for the participation of all sections to the end that the regionalization program will have a Union-wide base.

Recommendation (5): The Executive Secretary has been an active participant in all of the activities of the Special Committee on Regionalization and the Committee wishes here to express to him its appreciation. It is recommended that the office of AGU be utilized in developing the essential details of the plan for regionalization, reporting directly to the Executive Committee.

The Special Committee on Regionalization, having carried out the directive of the Executive Committee, requests that it now be discharged.

Attachment A

It is the hope and the desire to develop in AGU, a regional program of scientific activity that will meet the needs and desires of the members to permit the organization to attain more nearly the goals of service to its members and to the broad field of geophysics that have been set. It is recognized that to permit this, there must be extensive member-participation in activities; the virility of the organization springs from the spontaneous activities of the membership in fulfilling their organizational needs, not from the Secretariat or from the National Officers, however competent they may be. To this end, regional groups with a high degree of autonomy are to be fostered, the requirements being that the organization be loose and flexible, permitting the various Sections to take part in a given region or not, as the interests of the members in that region dictate. In planning a regional meeting, it should be understood that should only one section feel the need of a meeting and the other seven do not, the seven should not stand in the way of the one. Nor should any antecedent arrangements preclude participation by a new section.

To facilitate the implementation of an active plan of regionalization, the following suggestions are made:

(1) The plan for regionalization and the tentative boundaries indicated shall be published in the Transactions with invitations for comment and support by the membership following which officers of the Union and of the Sections shall get into touch with persons in the several regions who might be interested in implementing the plan in the region in the several fields of Geophysics.

(2) On the basis of the responses received, regional committees and the chairmen shall in the first instance be appointed by the President of AGU in consultation with the Section Presidents. The terms of these committees will conform to the term of the elected Union officers. Each committee shall consist of at least one representative of each Section in which active interest is indicated and shall not have more than nine members. It is understood that the representative(s) of each active Section, acting in collaboration with the President of the Sections, shall utilize the services of such other members as seem desirable, with one of the representatives of the Section as chairman, to act as the Section Regional Committee.

(3) Once the Committee is established, it shall organize, designate one of its members as Regional Secretary, draw up By-Laws that conform with the Statutes and By-Laws of the Union (tentative sample By-Laws will be sent to organizing regions) to be approved by the Executive Committee of the Union. Within the scope of these By-Laws, it shall proceed on a self-perpetuating, autonomous basis, arranging meetings and programs to provide the needs of the membership of the Region.

(4) Should a Committee at any time fail in its functions or fail to provide for its succession, it may be reactivated by the President of AGU acting in consultation with the officers of the Sections in the same way that the Committee is designated in the first instance.

REPORT OF REPRESENTATIVE OF AGU TO THE UNITED NATIONS SCIENTIFIC CONFERENCE ON THE CONSERVATION AND UTILIZATION OF RESOURCES, AUGUST 17 TO SEPTEMBER 6, 1949

The United Nations Scientific Conference on the Conservation and Utilization of Resources (UNSCCUR) was held at Lake Success, New York on August 17 to September 6, 1949. It is estimated that more than 700 scientists, engineers, and conservationists attended the conference. About 45 different countries were represented at the meetings.

The chief purpose of the conference was to provide for the exchange of experience on the techniques of the conservation and utilization of resources. Conferees participated as individuals and not as representatives of their governments or organizations. The conference was scientific rather than policy-making. It had no power to bind governments and will not make recommendations nor attempt to reach international agreements on policies. Emphasis was placed on the practical application of science to resource management and human use rather than the details of scientific research.

The meetings consisted of half-day sessions in each of the different fields of resources, as follows:

Forest Section - 7 sessions with 75 papers.
Fuels and Energy Section - 10 sessions with 65 papers.
Land Section - 14 sessions with 120 papers.
Minerals Section - 8 sessions with 55 papers.
Water Section - 8 sessions with 80 papers.
Wildlife and Fish Section - 7 sessions with 70 papers.
In addition to the section meetings there were 18 plenary sessions.

Preliminary copies of the papers were distributed to the conferees in advance of the meetings. The consideration of each paper at the meeting was limited to an abstract and discussion.

It is understood that the papers and discussions are to be published by the United Nations, with a separate volume covering the papers in each section. Those interested in the publications should write the Secretariat, UNSCCUR, United Nations, Lake Success, New York.

R. M. Leggette

REPORT OF REPRESENTATIVE OF AGU TO THE SEVENTY-FIFTH ANNIVERSARY OF THE FOUNDING OF THE COLORADO SCHOOL OF MINES, SEPTEMBER 29 TO OCTOBER 1, 1949

On September 29, 30, and October 1, the Colorado School of Mines, situated just outside of Golden, celebrated its Seventy-Fifth Anniversary. This meeting proved to be a great success as was justly anticipated by all. Visitors at this commemoration included Julius A. Krug, the Secretary of the Interior, and representatives of universities, colleges, and scientific societies. I had the honor of representing the American Geophysical Union.

Thursday afternoon, following the academic procession, Convocation was held at Steinhauer Field House. The delegates and visitors were welcomed by the President of the School and greetings were extended by the Governor of the State and the President of the University of Colorado. The address was given by Carey Croneis, President of Beloit College, who chose as his topic, "Men of Mettle." The evening address, at the banquet which followed, was given by Julius A. Krug.

The Friday and Saturday sessions were devoted to technical conferences. S. G. Lasky of the U. S. Geological Survey gave an interesting talk on a relationship he had developed between tonnage and grade of ore for predicting new ore supplies.

R. W. Goranson

Distribution of Transactions, International Association of Hydrology, Washington General Assembly, 1939--A limited supply of the *Transactions* of the 1939 General Assembly of the International Association of Hydrology have been made available to the United States. While normally a considerably larger number of copies would have been distributed, in this instance the plates for the *Transactions* were destroyed during the war. The copies which have been received have been deposited in the files of the Section of Hydrology and the American Geophysical Union and in selected libraries throughout the country. Any person desiring an opportunity to review these *Transactions* should arrange with his own library to secure a copy on an inter-library loan from one of the repository libraries. The distribution of copies is as follows:

California Institute of Technology Library,
Pasadena, California
University of Washington Library,
Seattle 5, Washington
Georgia Institute of Technology Library,
Atlanta, Georgia
Chief Engrs. Technical Library,
U. S. Bureau of Reclamation,
Denver Federal Center,
Denver, Colorado
Engineering Societies Library,
33 West 39th Street,
New York, N. Y.
University of Texas Library, Austin, Texas
Tennessee Valley Authority Library,
Knoxville, Tenn.
Library, Massachusetts Institute of Technology,
Cambridge 39, Mass.
University of Minnesota Library,
Minneapolis, Minnesota
Library of Congress, Washington, D. C.
U. S. Weather Bureau Library, Washington, D. C.
Library, Division of Irrigation, Univ. of California,
Davis, Calif.
John Crerar Library, Chicago, Ill.

American Standards Association--Fred Anderegg, AGU representative on the Committee on Photography Z38 of the ASA advises that the latest approved standards are as follows:

Z38.8.23-1949, X-ray sheet film hangers (clip type).

Z38.7.14-1949, specifications for lantern slide projectors. This standard takes into consideration illumination, lenses, stray light, slide temperature, and slide carrier.

Z38.1.29-1949, dimensions for professional portrait and commercial sheet film (centimeter sizes).

Fred Anderegg

Transactions, American Geophysical Union Volume 30, Number 6 December 1949

SPECIAL ANNOUNCEMENTS

LIST OF OFFICIAL NOMINEES FOR OFFICERS OF THE UNION AND OF THE SECTIONS FOR THE TRIENNIUM JULY 1, 1950 TO JUNE 30, 1953

Explanatory note: In accordance with the Statutes and By-Laws as amended to April 30, 1948, elections by mail ballot are to be held in the first part of 1950. The Committees on Nominations were published in the Transactions of August 1949, page 627. The Executive Committee of the Union has established procedures for nomination and election of officers of the Union, as published in the December 1946 issue of the Transactions, page 910. These are as follows: (1) Nominations shall be initiated by a small Nominating Committee consisting of three or five members, appointed by the President. (2) At least two persons shall be nominated for each of the offices of President, Vice-President, and General Secretary. (3) Such nominations shall then be submitted by the Nominating Committee to the Executive Committee, which body may accept the report, or add other nominees for such offices. It will then proceed to select by secret ballot not less than two official nominees for each office. (4) Such nominations shall then be announced to the membership, sufficient time being provided before election to permit further nominations by petition when signed by one per cent (46 at present) of entire membership, it being mandatory that nominations by petition be added to the official nominations. (5) Ballots containing official nominees and those submitted by petition shall be mailed to the active membership and such ballots, postmarked before a specified date, shall be marked and forwarded by the membership to the General Secretary. (6) The General Secretary within ten days after the specified date shall turn over all such ballots for tallying to a Committee of Tellers consisting of one member selected from each of the eight sections and one member from the Executive Committee. (7) The Committee of Tellers shall make report to the General Secretary within ten days, showing the result of the ballot. (8) A plurality of votes cast shall elect. (9) Consent of each candidate is to be obtained before placing his name on the ballot. (10) The Sections shall be urged to adopt similar procedures.

Similar Section procedures were established and were published in the Transactions of December 1946, with amendments covering Seismology and Hydrology in the Transactions of August 1949, page 627. They will not be repeated in full here. All provide for nominations by petition, the number of member petitioners affiliated with the Section being as follows: Geodesy, ten members; Seismology, 13 members; Meteorology, 25 members; Terrestrial Magnetism and Electricity, one per cent of those affiliated with the Section (ten members at present); Oceanography, ten members; Volcanology, one per cent of those affiliated with the Section (eight members at present); Hydrology, 25 members; and Tectonophysics, 15 members.

Please note that nominations by petition must include written consent from the nominee to be transmitted to the office of AGU with the petition.

The following time schedule for nominations and elections has been established.

By November 10, 1949, steps (1) to (3) and step (9) of procedure must be complete for the official nominees.

In Transactions of December, 1949, publish list of official nominees with explanatory note.

By February 1, 1950, nominations by petition must be in the office of AGU with written consent of nominees.

By March 1, 1950, ballots carrying names of official and petition nominees, will be mailed to the membership. A brief biographical sketch relating to each nominee will accompany, but not be a part of the ballot.

On March 31, 1950, balloting will close. Ballots must be postmarked not later than that date and be received in the office of AGU not later than April 4, 1950 in order to be counted.

By April 10, 1950, ballots will be turned over to the Committee of Tellers.

By April 20, 1950, results of tally will be turned over to the General Secretary, results to be announced at the Annual Meeting in the opening days of May, 1950, and published in the Transactions in June, 1950.

Attention is called to the fact that Article 5 of the Statutes provides "that the President and Vice-President shall not be eligible for immediate reelection . . ." The incumbents, Walter H. Bucher and F. W. Reichelderfer, were both designated by the Executive Committee to complete unexpired terms of the late O. E. Meinzer and of H. U. Sverdrup, respectively, and have thus not been elected. They stepped into the breach at critical times, and the Executive Committee concurred with the Committee on Nominations that such emergency service should not preclude their nomination to the offices they are now filling.

The nominees are as follows (arranged alphabetically):

Union or Section	President	Vice-President	Secretary[a]
Union	Walter H. Bucher Ernst Cloos Maurice Ewing	Perry Byerly F. W. Reichelderfer L. B. Slichter	K. Hilding Beij[a] J. Putnam Marble[a] J. Frank Shairer[a]
Geodesy	Harry H. Hess Floyd W. Hough	Albert J. Hoskinson Herman J. Shea	Frank L. Culley . . . .
Seismology	Perry Byerly Charles F. Richter	Leonard M. Murphy Florence Robertson	Mary C. Rabbitt James T. Wilson
Meteorology	Benjamin Holzman	Hurd C. Willett	Woodrow C. Jacobs
Terrestrial Magnetism and Electricity	J. Wallace Joyce	Ellis A. Johnson Elliot B. Roberts Victor Vacquier	Leroy R. Alldredge H. Herbert Howe . . . .
Oceanography	A. C. Redfield Edward H. Smith	E. C. LaFond Roger R. Revelle	R. H. Fleming Norris Rakestraw
Volcanology	Esper S. Larsen, Jr.	George C. Kennedy Thomas P. Thayer	Felix Chayes . . . .
Hydrology	F. J. Veihmeyer	Merrill Bernard	Ray K. Linsley, Jr.
Tectonophysics	Robert Balk M. P. Billings	Francis Birch Francis J. Turner	Wilbur S. Burbank R. W. Chapman

[a] For General Secretary in the case of the Union.

Waldo E. Smith
Executive Secretary

Plan for regionalization--The attention of the membership is called to the plan for regionalization set forth on pages 936 to 939 in this issue. This is a very flexible plan permitting of the maximum of latitude in this connection, providing such Sections as have interest to regionalize in any of the several regions delineated, but at the same time putting none under any pressure to do so. The comments of all members are invited, first with respect to the regional boundaries suggested, and second with regard to your interest in developing activity in your region in your field or fields of interest.

As set forth in the report, it is now the policy of AGU to foster an effective and strong regional program of scientific activity to permit AGU to fulfill its purposes more fully. The organization exists only by and for its members to serve definite scientific needs so that through its activity its members may grow in usefulness to themselves and to society. Provision can be made so that this activity may be carried to a sub-regional or local level, as dictated by your needs and desires.

Let us have your constructive criticism and suggestions, and more especially work concerning what fields of endeavor you desire to be active in your vicinity. Send in your note to the office of AGU today.

Regional Meeting in California--The Twenty-Fifth Regional Meeting will be held in Davis, California, February 3 and 4, 1950, in accordance with the announcement on page 795 of the October, 1949 issue of the Transactions. The Committee for this meeting is F. J. Veihmeyer (Chairman), Division of Irrigation, University of California, Davis; E. M. Vernon (Chairman for Meteorology), San Bruno, California; and J. C. Marr (Chairman for Hydrology), 520 C Street, Davis, California. James H. Marsteller is serving on the Committee for the Section of Meteorology instead of E. H. Fletcher as announced in the October issue of the Transactions.

Thirty-First Annual Meeting--The Thirty-First Annual Meeting will be held in Washington, D. C., May 1 to 3, 1950. See full announcement in the October, 1949, issue of the Transactions, page 795, for details.